

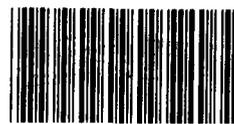
GAO

Report to the Chairman, Committee on  
Science, Space, and Technology,  
House of Representatives

July 1991

# AEROSPACE PLANE TECHNOLOGY

## Research and Development Efforts in Europe



144476

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United States  
General Accounting Office  
Washington, D.C. 20548

National Security and  
International Affairs Division

B-235387

July 25, 1991

The Honorable George E. Brown, Jr.  
Chairman, Committee on Science,  
Space, and Technology  
House of Representatives

Dear Mr. Chairman:

As requested by the former Chairman, we reviewed investment in foreign aerospace vehicle research and technological development efforts. Supporters of the National Aero-Space Plane Program in the Congress are concerned about foreign competition to the program and its impact on U.S. technological leadership. We briefed representatives of the former Subcommittee on Transportation, Aviation, and Materials (now part of the Subcommittee on Technology and Competitiveness), House Committee on Science, Space, and Technology, previously on the results of our review. This report discusses investment in European aerospace vehicle research and technological development efforts.

This report is the second in a planned series of reports on aerospace investment in foreign countries. We issued our first report, Aerospace Technology: Technical Data and Information on Foreign Test Facilities (GAO/NSIAD-90-71FS), on June 22, 1990. Subsequent reports will address aerospace investment in Japan and Australia and in the Soviet Union.

We are sending copies of this report to the Secretaries of Defense, State, Commerce, the Air Force, and the Navy; the Administrator, National Aeronautics and Space Administration; and the Directors, Defense Advanced Research Projects Agency, Strategic Defense Initiative Organization, Central Intelligence Agency, Office of Management and Budget, and Office of Science and Technology Policy in the Executive Office of the President. We are also sending copies of this report to other interested parties and will make copies available to others.

Please contact me at (202) 275-4268 if you or your staff have any questions concerning this report. Major contributors to this report are listed in appendix II.

Sincerely yours,

Nancy R. Kingsbury  
Director  
Air Force Issues

# Executive Summary

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## Purpose

U.S. leadership and preeminence in the research and development of aerospace plane technologies are being challenged by European countries. U.S. leadership and preeminence are based on the National Aero-Space Plane Program. However, congressional supporters of the program are concerned about foreign competition to the program and its impact on U.S. technological leadership.

As a result, the former Chairman of the House Committee on Science, Space, and Technology asked GAO to identify indicators to measure foreign countries' current state of aerospace plane technological development and progress. These indicators are (1) space policies and aerospace goals and objectives; (2) aerospace plane program objectives, design goals, schedules, and costs; (3) the current status and rate of progress in the development of critical technologies; (4) the funding for and the number and type of people involved with the programs; (5) test facilities and their capabilities; and (6) the existence of and interest in international cooperation. The former Chairman also asked GAO to collect data and information on the indicators.

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## Background

The National Aero-Space Plane Program, expected to cost more than \$5 billion between fiscal years 1986 and 1997, is a joint Department of Defense/National Aeronautics and Space Administration technology development and demonstration program to build and test the X-30 experimental plane. The program is to develop critical technologies for future hypersonic aerospace planes, which could achieve speeds greater than five times the speed of sound in air. The program also plans to build and test the X-30 to validate the critical technologies. These technologies include an air-breathing engine that requires air for combustion of its fuel; materials that are high-strength, lightweight, able to withstand high temperatures, and fully reusable; a fully integrated engine and airframe; and advanced computer programs to simulate the effects of the airflow around flight vehicles by solving a set of mathematical equations with a high-speed computer.

This report focuses on efforts in France, Germany, and the United Kingdom, since they are developing technologies and conducting feasibility studies for various concepts of operational aerospace planes. Also, efforts in The Netherlands, Belgium, and Italy are included because these countries support technology development efforts through national research and the use of their test facilities. In addition, this report discusses the efforts of the European Space Agency because it

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promotes cooperation in space research and technology among its 13 member countries.

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## Results in Brief

European countries are conducting feasibility studies and developing critical technologies needed for various concepts of operational aerospace planes primarily to achieve autonomy. However, no European country or the European Space Agency has officially approved any plan to build a spaceplane. The United States also has not approved a plan to build a spaceplane.

The United States is ahead of European countries in hypersonic aerospace plane technologies because of its more technologically challenging National Aero-Space Plane Program. However, European countries are making a determined effort to challenge U.S. superiority in hypersonics, particularly in engines and materials.

Current and planned levels of investment in air-breathing aerospace plane research and technological development efforts by European governments and industries are significantly less than current and planned U.S. government and industry investment in the National Aero-Space Plane Program.

European test facilities are adequate for fundamental research and current efforts in Europe. However, they are not adequate for large-scale testing or developing an aerospace plane.

Individually, European countries do not pose a serious challenge to U.S. preeminence in hypersonic aerospace plane technologies. No European country appears likely to develop and build an aerospace plane by itself because of the extensive technology and funding requirements. However, a major international collaborative effort under the European Space Agency, among European countries, or with Japan and/or the Soviet Union could be competitive with the National Aero-Space Plane Program. Although collaborative efforts with the United States on the National Aero-Space Plane Program appear unlikely, the program could benefit from European engine and materials technologies and the use of European test facilities.

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## Principal Findings

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### European Aerospace Plane Programs Are Primarily Concept Studies

France, Germany, and the United Kingdom are each developing the technologies required for various concepts of an aerospace plane to secure independent manned access to space, reduce the cost of launching payloads into orbit, and ensure a competitive role in future high-speed commercial transport aircraft markets. Principal concepts include France's Space Transportation System 2000 and Reusable Air-Breathing Transport System-Horizontal Landing, Germany's Saenger II, and the United Kingdom's Horizontal Takeoff and Landing vehicle. Each concept is being designed to take off horizontally from a runway, reach hypersonic speeds, attain orbit, and return to land on a runway.

### The United States Is Ahead of Europe in Hypersonic Technology

The United States is ahead of European countries in the development of three critical technologies: air-breathing engines, materials, and advanced computer programs and high-speed computers used for design and testing. Moreover, the United States is the only country that has tested major large-scale components of an air-breathing aerospace plane.

### U.S. Investment Is Significantly Greater Than European Investment in Aerospace Plane Programs

U.S. government and industry have invested almost \$1.8 billion in the National Aero-Space Plane Program between fiscal years 1986 and 1990. France, Germany, and the United Kingdom have only invested a total of about \$125 million between 1982 and 1990 in various air-breathing aerospace plane concept studies. The U.S. government plans to spend about \$2.7 billion on the National Aero-Space Plane Program from fiscal years 1991 to 1997. Future U.S. industry contributions are expected to be marginal. French, German, and British governments and industries plan to spend up to about \$217 million between 1990 and 1992 on various air-breathing aerospace plane programs. None has approved funding beyond 1992.

### European Test Facilities Are Inadequate for Developing and Testing Aerospace Planes

Although the United States is ahead in terms of facility size, productivity, and testing techniques, the Europeans' rate of progress in refurbishing and modifying old facilities and in building new facilities is significantly greater than that of the United States. However, only with the development of better test facility instruments and more trained

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personnel, together with the renovation and modification of older facilities and construction of new facilities, will adequate support be available in Europe for testing aerospace planes.

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### International Hypersonic Collaborative Effort Could Be Competitive With the United States

European governments, with the support of industries, are developing vehicle concepts first, on a national basis, before seeking international partners or making a proposal to the European Space Agency. Development of an experimental plane would probably be an international effort, since no European country is capable of developing and building an aerospace plane alone due to extensive technological requirements, tremendous costs, and lack of adequate test facilities. Any future operational aerospace plane built in Europe would also be an international effort, probably under the European Space Agency. However, the combined convergence of national interests, expertise, approaches, funding, and sharing of test facilities involving the European Space Agency, European countries, Japan, and/or the Soviet Union in a major international collaborative effort in hypersonics could, in the long term, prove to be competitive with the National Aero-Space Plane Program.

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### Recommendations

GAO is not making recommendations in this report.

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### Agency Comments

GAO did not obtain official agency comments on this report. However, GAO provided a draft of this report to Department of Defense and National Aeronautics and Space Administration officials and incorporated their comments where appropriate.

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**Abbreviations**

CARGUS	Cargo Upper Stage
EARL	European Advanced Rocket Launcher
EURECA	European Retrievable Carrier
FALKE	Fallkoerpererprobung (Flight Model Drop Test)
GAO	General Accounting Office
HORUS	Hypersonic Orbital Upper Stage
HOTOL	Horizontal Takeoff and Landing
HYTEX	Hypersonic Technology Experimental
LART	Luftatmender Raumtransporter (Air-Breathing Space Transporter)
MBB-ERNO	Messerschmitt-Boelkow-Blohm/ERNO Raumfahrttechnik
NASP	National Aero-Space Plane
PLATO	Platform Orbiter
scramjet	supersonic combustion ramjet
STAR-H	Systeme de Transport Aerobie Reutilisable a Decollage et Atterrissage Horizontaux (Reusable Air-Breathing Transport System-Horizontal Landing)
STS	Systeme de Transport Spatial (Space Transportation System)

# Introduction

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U.S. aeronautical leadership and preeminence are being challenged by European countries' development of technologies for operational aerospace vehicles. Currently, U.S. aeronautical leadership and preeminence in hypersonics<sup>1</sup> are based on the National Aero-Space Plane (NASP) Program. However, NASP supporters in the Congress are concerned that without a major and sustained initiative in hypersonics, the U.S. lead in aeronautics will be challenged by other countries.

The European Space Agency, France, Germany, and the United Kingdom are each developing the technologies and conducting feasibility studies for various concepts of operational aerospace vehicles. Italy, The Netherlands, and Belgium are also supporting this technology development, and their facilities are being used to test various concepts of aerospace vehicles.

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## U.S. Aeronautical Preeminence in Hypersonics

U.S. aeronautical preeminence in hypersonics is currently based on the NASP Program—a more than \$5 billion joint Department of Defense/National Aeronautics and Space Administration technology development and demonstration program to provide the technological basis for future hypersonic flight vehicles. The program plans to build and test a manned experimental flight vehicle, the X-30, to validate critical or enabling technologies by demonstrating sustained hypersonic cruise and single-stage-to-orbit space launch capabilities. The X-30 is being designed to take off horizontally from a conventional runway, reach hypersonic speeds of up to Mach 25 (25 times the speed of sound, which is orbital velocity), attain low earth orbit, and return to land on a conventional runway. The NASP Program is expected to develop and demonstrate the technology for future NASP-derived vehicles that will have technical, cost, and operational advantages over existing military and commercial aircraft and space launch systems.

The X-30 will be an experimental flight vehicle. It will not be a prototype or operational vehicle. The X-30 has no operational mission or requirements. Also, the X-30 will not be a full-scale version of future operational aerospace vehicles. Potential users of a future aerospace

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<sup>1</sup>Technical terms are defined in the glossary.

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plane probably will not develop specific missions or identify firm operational requirements until the X-30's capabilities have been demonstrated.<sup>2</sup>

Many NASP supporters in the Congress are concerned that terminating or delaying the NASP Program will jeopardize the U.S. lead in hypersonics, whereas others believe that a slower NASP technology maturation phase will not adversely affect U.S. leadership. Still others believe that without a major and sustained initiative in hypersonics, U.S. aeronautical leadership and preeminence will be challenged by other countries' development of technologies for operational aerospace vehicles. A key factor in the National Space Council's July 1989 recommendation to continue the NASP Program, but at a slower pace than the original schedule, is the desire to maintain the U.S. lead in aerospace technologies into the 21st century.

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## Principal European Aerospace Vehicle Concepts or Systems

The European Space Agency, France, Germany, and the United Kingdom are each conducting research and development on various aerospace vehicle concepts or systems. The principal concepts include the European Space Agency's Hermes spaceplane (originally a French national program), Germany's Saenger II Advanced European Space Transportation System, and the United Kingdom's Horizontal Takeoff and Landing (HOTOL) vehicle. These concepts are briefly described below and are discussed in more detail in chapter 3.

The European Space Agency's Hermes spaceplane is being developed as an operational, manned, reusable, shuttle-like reentry winged vehicle. Expected to be launched vertically by the Ariane 5 rocket booster, the spaceplane would return to earth and land horizontally on a runway. Although Hermes would not be an air-breathing aerospace plane, it would serve as a technology demonstrator, have an operational capability, and be an intermediate step in developing a future European air-breathing aerospace plane.

Germany's Saenger II is being developed as a two-stage-to-orbit space launch vehicle that would be capable of horizontal takeoff from and landing at European airports. The first stage is expected to be an air-breathing hypersonic aircraft powered by a turboramjet that could also

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<sup>2</sup>For a detailed and technical description of the NASP Program, including U.S. government and industry investment in the program, see our report, National Aero-Space Plane: A Technology Development and Demonstration Program to Build the X-30 (GAO/NSIAD-88-122, Apr. 27, 1988).

provide the technological basis for a future European hypersonic passenger aircraft. The second stage would consist of either a manned or unmanned reusable reentry winged vehicle. Both second-stage vehicles would be powered by rocket engines.

The United Kingdom's HOTOL vehicle is being designed as an unmanned single-stage-to-orbit, fully recoverable, and reusable space launch vehicle. HOTOL is being designed to be launched horizontally by a rocket-powered wheeled-trolley or sledge from a conventional runway, reach hypersonic speeds up to Mach 25, attain low earth orbit, and glide back to earth and land horizontally on a conventional runway.<sup>3</sup> An interim version of HOTOL that uses only rocket propulsion is also being designed to be air-launched by the Soviet Union's Antonov An-225 heavy-lift transport aircraft.

## Indicators of Aerospace Vehicle Technological Development and Progress

The indicators we used to measure foreign countries' interest, commitment, and capability to develop and build an air-breathing aerospace vehicle and the current state of aerospace vehicle technological development and progress were selected based on the interests of representatives of the former Subcommittee on Transportation, Aviation, and Materials (now part of the Subcommittee on Technology and Competitiveness), House Committee on Science, Space, and Technology, and on discussions with U.S. government and aerospace industry program managers, scientists, and engineers. These indicators are

- foreign governments' space policies and aerospace goals and objectives, if any, for developing, or participating in the development of, air-breathing aerospace vehicles;
- current and future aerospace vehicle program objectives, design goals, schedules, and costs;
- the current status and rate of progress in the development of enabling technologies;
- investment by foreign governments, industries, and universities in aerospace vehicle research and technological development efforts in terms of funding and the number and type of people working on these efforts;
- test facilities and their capabilities; and
- international cooperation.

<sup>3</sup>According to the Director of the NASP Interagency Office, HOTOL would not be a true single-stage-to-orbit aerospace vehicle, since it would be launched by a rocket-powered wheeled-trolley or sledge, which is technically a booster vehicle. The Director suggested HOTOL could be considered a near-single-stage-to-orbit vehicle.

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## Enabling Technologies

Enabling technologies are critical to the successful development and demonstration of future hypersonic flight vehicles. These include an air-breathing propulsion system using, for example, a turboramjet or supersonic combustion ramjet (scramjet); advanced materials that are high-strength, lightweight, able to withstand high temperatures, and fully reusable; a fully integrated engine and airframe; and computational fluid dynamics and supercomputers for aerodynamic, structural, and propulsion system design.

Failure to successfully develop and demonstrate any of the enabling technologies could adversely affect European aerospace vehicle programs. Also, the enabling technologies must be fully integrated, since the design of one component can impact the performance of another component. Enabling technologies are discussed in more detail in chapter 4.

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## Role of the European Space Agency

The European Space Agency, which is headquartered in Paris, provides for and promotes cooperation in space research and technology and space applications among its member countries.<sup>4</sup> The European Space Agency prepares long-term plans for European space research. The most recent plan, approved in 1987, includes development of the Ariane 5 launch vehicle, Columbus space infrastructure,<sup>5</sup> and Hermes spaceplane.

The European Space Agency has both mandatory and optional programs. Mandatory programs include technological research, investment in facilities, and scientific satellites. Members must contribute to such activities based on their countries' average national incomes. Optional programs include applications satellites, space transportation systems, a space station, and space platforms. Members contribute to these programs based on their interest. For example, France is the largest contributor to the Hermes spaceplane, and Germany is the largest contributor to the Columbus program.

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<sup>4</sup>European Space Agency members are Austria, Belgium, Denmark, France, Germany, Ireland, Italy, The Netherlands, Norway, Spain, Sweden, Switzerland, and the United Kingdom. Finland is an associate member, and Canada participates in some European Space Agency programs under a cooperative agreement.

<sup>5</sup>The Columbus space infrastructure consists of three projects. The Columbus Attached Pressurized Module, a laboratory that is to be launched and serviced by the U.S. space shuttle, would join three similar modules (two American and one Japanese) in becoming a permanent part of the planned U.S. space station. The Columbus Free-Flying Laboratory, an autonomous laboratory designed to fly in the same orbital plane as the space station, is expected to be launched in 1998 by an Ariane 5 booster and would primarily be maintained and serviced in orbit by astronauts flying on the Ariane 5/Hermes space transportation system. The third element, the Columbus Polar Platform, is scheduled to be launched by Ariane 5 in 1997.

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European Space Agency members' research organizations and aerospace companies participate in the optional activities under an industrial policy referred to as "Juste Retour," or just return. Under this policy, European Space Agency contracts are awarded to each member's aerospace industry in roughly the same proportion as the government's contribution to the European Space Agency's optional programs.

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## Organizational Roles and Responsibilities

The roles and responsibilities of the principal government organizations and companies involved in aerospace vehicle research and technological development in France, Germany, the United Kingdom, Italy, The Netherlands, and Belgium are discussed below.

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### France

The Ministries of Research and Technology; Defense; and Post, Telecommunications, and Space share responsibilities for space activities in France. The Centre National d'Etudes Spatiales, or National Center for Space Studies, manages France's space program. The Center's role is to coordinate research and development, manage industrial implementation of major French space programs, ensure the competitiveness and proper marketing of French space products, establish and operate the infrastructure required, and encourage international cooperation.

The Office National d'Etudes et de Recherches Aerospatiales, or National Office for Aerospace Studies and Research, is France's aerospace research organization. The Office's mission is to develop, orient, and coordinate France's aerospace research; build, design, and implement the means necessary to carry out the research; and make the results available. The Office conducts fundamental and applied research and provides direct technical assistance to industry. The Office serves as a link between scientific work and aerospace manufacturers' civil and military programs in the design and production stage.

Principal French aerospace companies involved in air-breathing aerospace vehicle research and development include Aerospatiale; Avions Marcel Dassault-Breguet Aviation; the Societe Nationale d'Etude et de Construction de Moteurs d'Aviation, or National Company for the Study and Construction of Aviation Engines; and the Societe Europeenne de Propulsion, or European Propulsion Company, a subsidiary of the National Company for the Study and Construction of Aviation Engines. The French government has controlling interest in all four companies.

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## Germany

The Bundesministerium fuer Forschung und Technologie, or Federal Ministry for Research and Technology, is responsible for developing Germany's aerospace goals and objectives and for conducting its space activities.

The Deutsche Agentur fuer Raumfahrtangelegenheiten, or German Space Agency, coordinates and manages all of Germany's space activities. The Agency has no operational or research capabilities. However, it assists the German government in developing national space policy and plans, oversees the implementation of German space programs, carries out industrial policies for government-funded space programs, and represents German space interests by serving as a liaison with international organizations, particularly with the European Space Agency. Although the Agency is government owned and receives its funding from the German government, it operates as a private corporation.

The largest research and testing establishment in Germany is the Deutsche Forschungsanstalt fuer Luft- und Raumfahrt, or German Aerospace Research Establishment, which is responsible for implementing Germany's national space program. Its primary task is to establish a scientific and technical basis for the development and utilization of future aircraft and space vehicles. The Establishment is an independent, non-governmental organization that works closely with government and serves as an intermediary between government and industry. In contrast to the French approach, the Establishment is not involved in commercial space activity.

The Deutsche Forschungsgemeinschaft, or German Research Association, funds university research in critical or enabling technologies needed for the development of a future aerospace vehicle.

Major German companies involved in aerospace research and development and their primary areas of specialization are Messerschmitt-Boelkow-Blohm (overall system integration, propulsion, flight management, and aerothermodynamics), Motoren- und Turbinen-Union (propulsion), and Dornier (systems, materials, and structures). These three companies plus Telefunken Systemtechnik merged, creating the Deutsche Aerospace company, which is owned by Daimler Benz. Despite antitrust concerns, the German government approved the merger in part so that Deutsche Aerospace would be more competitive with aerospace companies in France, the United Kingdom, and the United States.

Deutsche Hermes was formed at the direction of the German government to ensure that German industry receives Hermes spaceplane contracts from the European Space Agency that are commensurate with the government's 27 percent contribution to the European Space Agency for Hermes' development. However, to streamline the Hermes program, the European Space Agency announced the creation of a new management company, Euro-Hermespace, to oversee full-scale development and production of Hermes. Euro-Hermespace participants include the four principal aerospace companies developing Hermes (Aerospatiale, Avions Marcel Dassault-Breguet Aviation, Deutsche Aerospace, and Aeritalia-Societa Aerospaziale Italiana, or Aeritalia-Italian Aerospace Corporation).<sup>6</sup> Deutsche Hermes was not included as a participant.

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## United Kingdom

The British National Space Centre is responsible for developing and implementing civilian aerospace goals and objectives for the United Kingdom. The Centre is also responsible for managing the British space budget, coordinating the British space program, and serving as a liaison with industry.

The Royal Aerospace Establishment supports the British Department of Trade and Industry and Ministry of Defence, among others, by performing technical studies to develop future government space strategies, providing project offices and technical support for space projects, conducting research programs, coordinating international liaisons for space programs, operating space facilities, and supporting industry. The Establishment also supports the British National Space Centre in its formulation and operation of British national, bilateral, and European Space Agency space programs.

Major British companies involved in aerospace vehicle research and development include British Aerospace and Rolls-Royce. British Aerospace's primary expertise is developing and integrating structures. Rolls-Royce specializes primarily in propulsion.

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## Italy

The Agenzia Spaziale Italiana, or Italian Space Agency, develops Italy's space policy, manages its space programs, and implements Italy's 5-year National Space Plan. Italy's participation in European Space Agency programs, however, requires the approval of the Italian Ministry of Science and Technology.

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<sup>6</sup>In December 1990 Aeritalia and Selenia merged, creating Alenia.

The Centro Italiano Ricerche Aerospaziali, or Italian Aerospace Research Center, is responsible for aerospace research. Although jointly owned by major Italian aerospace companies and the Naples Regional Government, the Center is now becoming essentially a governmental facility with contributions from its owners. The Center assists Italian industry's participation in European programs and expects to conduct tests and research for industry in the near future once major experimental facilities are constructed.

Principal Italian aerospace companies include Alenia (formed by the December 1990 merger of Aeritalia and Selenia), Fiat Aviazione, and Societa Nazionale Industria Applicazione-Bomprini Parodi Delfino, or Bomprini Parodi Delfino-National Industrial Applications Corporation. Aeritalia concentrates on structures and thermal control, whereas Selenia focuses on telecommunications and satellites. Fiat Aviazione's specialties include airframe structures, propulsion, microgravity, and turbopumps. Bomprini Parodi Delfino-National Industrial Applications Corporation is primarily involved in propulsion and manufacturing materials such as carbon-carbon.

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## The Netherlands

The Nederlands Instituut Voor Vliegtuigontwikkeling en Ruimtevaart, or Netherlands Institute for Aerospace Programs, promotes industrial aerospace activities for the Dutch government primarily through contracts, aerospace development projects, and technological research programs. Although it has no test facilities of its own, the Institute provides industrial management and coordination of Dutch space activities. The Institute also provides recommendations on aerospace matters to the policy-making Governmental Interdepartmental Committee on Space, Research, and Technology.

The Nationaal Lucht-en Ruimtevaartlaboratorium, or National Aerospace Laboratory, is the principal institution for aerospace research and development in The Netherlands. The Laboratory's primary mission is to provide scientific support to aerospace industries and organizations.

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## Belgium

The Science Policy Office, under the authority of the Ministry of Science Policy, manages Belgium's space program. It also represents Belgium in the European Space Agency and with international partners.

The von Karman Institute for Fluid Dynamics is an international non-profit scientific organization founded under the auspices of the North

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Atlantic Treaty Organization's Advisory Group for Aerospace Research and Development. It conducts postgraduate training and research in fundamental and applied fluid dynamics. The Institute has important shock tunnel facilities for testing models of aerospace vehicles.

Belgian companies that have a wide range of technical expertise in space-related activities, particularly in development and production testing, include Fabrique Nationale Moteurs, or Belgian Engine Works (engine components); Societe Anonyme Belge de Constructions Aeronautiques, or Belgian Aeronautical Construction Corporation (manufacture of structures and components); and Societe Nationale de Construction Aerospatiale, or National Corporation for Aerospace Construction (structures and materials). Belgian industry formed the Groupement Belge des Constructeurs de Materiel Aerospatiale, or Belgian Association of Manufacturers of Aerospace Equipment, to compete more favorably for Belgian and international aerospace contracts.

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## Objectives, Scope, and Methodology

The former Chairman of the House Committee on Science, Space, and Technology asked us to identify indicators (discussed on p. 12) to measure foreign countries' current state of aerospace vehicle technological development and progress. The former Chairman also asked us to collect data and information on foreign government and industry investment in aerospace vehicle research and technological development efforts, focusing on those critical or enabling technologies that could allow foreign countries to develop and build future aerospace vehicles. The former Subcommittee on Transportation, Aviation, and Materials (now part of the Subcommittee on Technology and Competitiveness), which has authorization and oversight responsibility for the National Aeronautics and Space Administration's aeronautical research and technology programs, including the NASP Program, is particularly concerned about foreign competition to the NASP Program and future NASP-derived operational aerospace planes. NASP supporters in the Congress are concerned that, without a major and sustained initiative in hypersonics, the U.S. lead in aeronautics will be challenged by other countries.

This report is the second in a planned series of reports on aerospace investment in foreign countries. Our first report was in response to the Committee's request that we provide it with technical data and information on foreign aerospace test facilities to assess foreign countries' research, development, and testing capabilities for future aerospace

vehicles.<sup>7</sup> The Committee is particularly interested in the potential use of key foreign test facilities by the NASP Program. Subsequent reports will address aerospace investment in Japan and Australia and in the Soviet Union.

The scope of our review was primarily limited to future air-breathing aerospace vehicles, since they could provide competition to NASP or future NASP-derived operational vehicles. Our review included France, West Germany,<sup>8</sup> and the United Kingdom, since each of these countries are developing technologies and conducting feasibility studies for various concepts of operational aerospace vehicles. In addition, we included facilities (such as wind tunnels) in The Netherlands, Belgium, and Italy. Although these countries do not have national programs to develop and build air-breathing aerospace vehicles, they support the technology development and allow other countries and the European Space Agency to use their test facilities to conduct research and development of such vehicles.

We collected technical data and information on test facilities, their capabilities, and the number of people working on aerospace vehicle research and development in those countries included in our review. Facilities include (1) wind tunnels and shock tunnels; (2) air-breathing propulsion test cells (engine test facilities for ramjets and scramjets); (3) aerothermal test facilities; (4) aeroballistic and impact ranges; (5) advanced materials research, development, production, and fabrication laboratories; and (6) aerodynamic computation facilities (supercomputers). We also collected cost information on test facilities, including construction, replacement, annual operating, and user costs, where available.

Our methodology involved reviewing studies and pertinent documents and interviewing appropriate officials in Washington, D.C., at the Departments of Defense, the Air Force, State, and Commerce; the

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<sup>7</sup>For technical data and information on principal European, Japanese, and Australian aerospace test facilities (wind tunnels and air-breathing propulsion test cells) and their capabilities, see our report, *Aerospace Technology: Technical Data and Information on Foreign Test Facilities* (GAO/NSIAD-90-71FS, June 22, 1990).

<sup>8</sup>The Federal Republic of Germany and the German Democratic Republic were reunified on October 3, 1990. Although we conducted review work in West Germany, we refer to it as Germany throughout this report.

Defense Advanced Research Projects Agency; NASP Interagency Office;<sup>9</sup> National Aeronautics and Space Administration; Central Intelligence Agency; and the Office of Science and Technology Policy in the Executive Office of the President. We also met in Washington, D.C., with officials of Gellman Research Associates, Inc., of Jenkintown, Pennsylvania, to discuss their methodology for analyzing government support for civil aeronautical research and technology expenditures in France, the United Kingdom, Germany, The Netherlands, and Japan; and the Washington Office of the German Aerospace Research Establishment and German Space Agency.

We also visited the NASP Joint Program Office, the Foreign Technology Division of the Air Force Systems Command, and Air Force Wright Aeronautical Laboratories, Wright-Patterson Air Force Base, Dayton, Ohio; Arnold Engineering Development Center and the Foreign Technology Division of the Air Force Systems Command, Arnold Air Force Base, Tullahoma, Tennessee; and Lovelace Scientific Resources, Inc., Albuquerque, New Mexico, to discuss its approach and methodology for comparing world civil space programs.

We met with Air Force, National Aeronautics and Space Administration, and contractor officials, scientists, and engineers to help us develop our approach and methodology, determine key enabling technologies, and identify specific data requirements needed to measure the status of a country's technological maturation and capability to develop and build a future air-breathing aerospace vehicle.

Our methodology also involved reviewing studies and pertinent documents; interviewing appropriate U.S. Embassy, international organization, and foreign government, industry, and university officials; and visiting key test facilities in France, Germany, the United Kingdom, The Netherlands, Belgium, and Italy. The organizations and locations where we conducted our review work in Europe are discussed below.

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<sup>9</sup>Three offices have responsibility for the NASP Program. The NASP Interagency Office in Washington, D.C., coordinates the NASP Program among participating agencies and military services. It also provides oversight, furnishes policy guidance, and maintains support for the program within the U.S. government. The NASP Joint Program Office at Wright-Patterson Air Force Base, Dayton, Ohio, is responsible for overall management and coordination of the NASP Program. It also implements the technical program and manages the contracts. The NASP National Program Office in Seal Beach, California, integrates the prime contractors into one program office under a single program director. It directs the contractor team's effort through a single contract with the U.S. government, provides program guidance, ensures adequate contractor team resources, reviews program progress, and resolves contractor team disputes.

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**France**

We conducted review work in Paris at the U.S. Embassy, U.S. Mission to the Organization for Economic Cooperation and Development, Organization for Economic Cooperation and Development Headquarters, National Center for Space Studies, National Office for Aerospace Studies and Research, North Atlantic Treaty Organization Advisory Group for Aerospace Research and Development, European Space Agency Headquarters, European Propulsion Company, and National Company for the Study and Construction of Aviation Engines. We also conducted work in Les Mureaux at Aerospatiale and in Saint Cloud at Avions Marcel Dassault-Breguet Aviation.

We also visited the National Office for Aerospace Studies and Research's S1MA (transonic) Wind Tunnel, S2MA (transonic and supersonic) Wind Tunnel, S3MA (trisonic) Wind Tunnel, S4MA (hypersonic) Wind Tunnel, and R4.3 (trisonic) Cascade Wind Tunnel at its Modane-Avrieux Centre in Modane.

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**Germany**

We conducted review work in Bonn at the U.S. Embassy, U.S. Air Force Research and Development Liaison Office, and Federal Ministry for Research and Technology; in Koln-Porz at the German Aerospace Research Establishment; in Friedrichshafen at Dornier; in Ottobrunn at Messerschmitt-Boelkow-Blohm; in Munich at the U.S. Consulate General and Motoren- und Turbinen-Union; in Aachen at the Rheinisch-Westfalischen Technischen Hochschule Aachen, or Rheinland-Westfalia Technical University of Aachen; and in Stuttgart at the University of Stuttgart.

We also visited several German Aerospace Research Establishment hypersonic vacuum tunnel facilities in Goettingen, wind tunnel and shock tunnel facilities at the Rheinland-Westfalia Technical University of Aachen, engine test stands at Motoren- und Turbinen-Union in Munich, and wind tunnel and altitude engine test facilities at the University of Stuttgart.

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**United Kingdom**

We conducted review work in London at the U.S. Embassy, U.S. Air Force European Office of Aerospace Research and Development, U.S. Air Force Research and Development Liaison Office-United Kingdom, the British National Space Centre, Rolls-Royce, and The Royal Society; in Stevenage at British Aerospace; in Southampton at The University of Southampton; and in Oxford at Oxford University.

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We also visited the Hypersonic Gun Tunnel, Light Piston Isentropic Compression Facility, and 12.5 centimeter Diameter Shock Tube at The University of Southampton and the Oxford University Gun Tunnel, Low-Density Wind Tunnel, and Isentropic Light Piston Tunnel at Oxford University.

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**The Netherlands**

We conducted review work in The Hague at the U.S. Embassy and in Amsterdam at the Netherlands Institute for Aerospace Programs and National Aerospace Laboratory.

We also visited the Duits-Nederlandse Windtunnel/Deutsche-Niederländischer Windkanal, or German-Dutch Low-Speed Wind Tunnel, at the National Aerospace Laboratory's Noordoostpolder site near Marknesse; the National Aerospace Laboratory's High-Speed (transonic) Wind Tunnel and Supersonic Wind Tunnel, flight simulator, and computer center in Amsterdam; and the European Space Agency's European Space Research and Technology Center in Noordwijk.

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**Belgium**

We conducted review work in Brussels at the U.S. Embassy, U.S. Mission to the European Communities, European Communities Headquarters, Belgian Aeronautical Construction Corporation, Belgian Engine Works, and the Belgian Association of Manufacturers of Aerospace Equipment; and in Rhode Saint Genese at the von Karman Institute for Fluid Dynamics. We did not meet with officials of the Belgian government, since it has no plans to participate in research, development, and testing of an aerospace plane.

We also visited the von Karman Institute Longshot Free Piston Tunnel ST-1 at the von Karman Institute for Fluid Dynamics.

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**Italy**

We conducted review work in Rome at the U.S. Embassy, Italian Space Agency, Italian Aerospace Research Center, and Associazione Industrie Aerospaziali, or Aerospace Industry Association; in Colleferro at Bomprini Parodi Delfino-National Industrial Applications Corporation; and in Turin at Aeritalia and Fiat Aviazione.

We provided a draft of this report to officials from the European Space Agency and foreign government and industry organizations in Europe and asked them to review, verify, and, if necessary, update the information. Their comments have been incorporated in the report where appropriate.

We used annual average exchange rates to convert foreign currencies into U.S. dollars.

We did not obtain official written agency comments on this report. However, we provided a draft of this report to officials from the Department of Defense and National Aeronautics and Space Administration and several U.S. experts in hypersonics for their review. We discussed the information presented in this report with these officials and experts and incorporated their technical and editorial comments where appropriate.

We conducted our review between March 1988 and October 1990 in accordance with generally accepted government auditing standards.

# European Space Policies and Aerospace Goals and Objectives

European countries' space policies do not specifically address research and development of air-breathing aerospace vehicles. However, their aerospace goals and objectives include plans for developing—or participating in the development of—a space transportation system motivated primarily by a desire for autonomy. The Europeans' objectives are to develop a more reliable space launch vehicle than the U.S. space shuttle that would secure an independent manned access to space and reduce the cost of launching payloads into orbit. The Europeans also plan to use the knowledge gained in hypersonic technology development programs to develop future high-speed commercial transport aircraft.

European governments and industries are conducting concept studies and developing the critical or enabling technologies necessary for future operational air-breathing aerospace vehicles through national programs. Development of a flight demonstrator to validate the technologies and actual flight testing of an aerospace vehicle are expected to require an international effort. Any future operational aerospace vehicle built in Europe would also be an international effort, probably under the European Space Agency.

## Space Policies and Aerospace Goals and Objectives for Developing Air-Breathing Aerospace Vehicles

European plans for developing a space transportation system are driven primarily by a desire for autonomy. Independent access to space has been a European (and particularly French) desire since the creation of the European Space Agency and its predecessors.

The desire for autonomy has been strengthened considerably by several events. We found a great deal of lingering resentment among Europeans who feel that they were treated unfairly by the United States in the Spacelab program, a major investment that Europe agreed to turn over to the National Aeronautics and Space Administration. Originally, the National Aeronautics and Space Administration planned to buy five more Spacelab units from the European Space Agency; however, only one was finally purchased. We also found European resentment over the National Aeronautics and Space Administration's cancellation of a space science mission<sup>1</sup> and the difficult negotiations over questions of partnership and access to the planned U.S. space station. Finally, the January 1986 Challenger accident made the Europeans realize that a failure of

<sup>1</sup>The International Solar Polar Mission is a joint U.S./European Space Agency mission that would make a polar orbit of the sun to study its magnetic field and solar winds. The United States canceled development of its spacecraft. The European Space Agency's instrumentation was finally launched by the U.S. space shuttle Discovery on the Ulysses mission in October 1990.

the U.S. space shuttle program has a ripple effect on other world space programs, including theirs, grinding many of them to a halt. The Europeans do not want to be put in such a vulnerable position again, one in which failure of the U.S. space transportation system incapacitates much of their own program.

No European government or the European Space Agency has officially approved any plans to build a spaceplane. The United States also has not approved a plan to build a spaceplane. In fact, no commitment exists to build the X-30 experimental vehicle. A decision on whether to build and test the X-30, based primarily on cost and the maturity of the technologies, is expected to be made in April 1993.

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## France

Access to space has been a long-standing priority in France. According to the National Aeronautics and Space Administration's European Representative, France's apparent but unstated goal is to achieve independent European manned access to space and for Europe to be a major player in space along with the United States and the Soviet Union.

France does not have a written policy concerning the development of an air-breathing aerospace vehicle, according to French officials. However, the Hermes spaceplane program began as a French national program before it was adopted by the European Space Agency. Although the National Center for Space Studies conducted a study of various aerospace vehicle concepts and propulsion systems, the study was exploratory and, according to Center officials, should not be viewed as a commitment by France to develop an air-breathing aerospace vehicle. Moreover, according to French officials, development of an aerospace plane in Europe would most likely be accomplished through the European Space Agency.

France's research in air-breathing aerospace vehicle technology and hypersonic flight is motivated by potential civilian applications, such as the development of a low-cost space transport system to succeed the European Space Agency's Hermes spaceplane and Ariane 5 launch vehicle. It is also motivated by potential military applications, such as a spaceplane or hypersonic cruise aircraft that could be launched from many different bases on short notice.

Aerospace vehicle research and development in France focuses on space transport systems that would become operational after 2010, since the Ariane 5 is expected to satisfy European requirements for launching

payloads into low earth orbit or geostationary transfer orbit until then. Similarly, the Hermes spaceplane is expected to satisfy European requirements for manned flights until 2010. According to a National Office for Aerospace Studies and Research official, a new space transport system would be needed only after 2010 to meet the growing demand in annual tonnage and launch frequency for potential civilian missions that include conducting experiments in orbiting manned vehicles; deploying orbital infrastructure; transporting astronauts and equipment to and from the space station and preparing for geostationary and interplanetary missions; launching, maintaining, repairing, and recovering satellites in low earth orbit; and conducting emergency rescue or repair operations in space. The key civilian requirements for a post-Hermes and Ariane 5 space transportation system are high reliability because of the crew on board, high versatility, and low cost.

Potential military missions for a spaceplane are being discussed by French officials. According to a National Office for Aerospace Studies and Research official, these missions could include launching, on short notice, nonrecoverable surveillance, communications, alert, or navigation satellites; launching recoverable equipment (such as ground inspection systems); low earth orbit missions including crew transfers, repairs, experiments, earth observation, and inspection of an object in space; and hypersonic flight in the atmosphere (above Mach 5) for strategic reconnaissance or long-range bombing. The key military requirements for a future space transportation system are short preparation time during a crisis, basing flexibility, and low cost.

According to National Office for Aerospace Studies and Research officials, research and development of an air-breathing aerospace vehicle will also result in technological spin-off applications such as aerothermal and structural computational fluid dynamics codes, advanced high-temperature materials, on-board software, and navigation and flight control equipment. These officials cautioned that direct spin-off for the development of a hypersonic airplane is unlikely because of safety constraints in handling fuel, takeoff noise, atmospheric pollution, and the need for profitability, which may require different technologies.

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## Germany

The Federal Ministry for Research and Technology is conducting a Hypersonic Technology Program, which outlines goals and objectives for conducting research and development of an air-breathing aerospace

vehicle. According to German government and industry officials, development of such a vehicle would most likely be accomplished through the European Space Agency.

Germany's strategic aerospace objectives are to develop a more cost-effective and reliable space transportation system than the U.S. space shuttle. According to the Hypersonic Technology Program, Germany intends to assume leadership responsibilities in the development of an aerospace plane. Although not part of the Hypersonic Technology Program, the knowledge gained in hypersonic technology will be used by Germany to develop future civilian high-speed transport aircraft above speeds of Mach 4. Moreover, according to a German government official and industry representatives, whether Saenger II becomes operational is not as important as its role in developing and maintaining a national research capability and training industry personnel.

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## United Kingdom

Although the British National Space Centre participated in an evaluation of the HOTOL aerospace vehicle concept proposed by British Aerospace and Rolls-Royce, the British government is not currently supporting the development of an air-breathing aerospace vehicle, according to Centre officials. The British government's participation in HOTOL's development ended in July 1988 when it elected not to fund further HOTOL research and development. British government officials are encouraging industry to fund and conduct future research and development efforts and to seek international partners. According to Centre officials, development of an air-breathing aerospace vehicle would most likely be conducted through the European Space Agency.

Space transportation systems have always been a relatively low priority for the British government, according to Centre officials. The United Kingdom is one of the few countries where industry leads the government in aerospace investment. The British government is encouraging the commercialization of the Columbus space infrastructure and HOTOL. The British government initially supported the HOTOL concept as an economical space launch system, since it considers low-cost access to space as important as the commercialization of space.

According to the British National Space Centre, the British government elected not to join the European Space Agency's optional Ariane 5 and Hermes programs because British government officials believe that the European Space Agency's desire for European autonomy in manned space flight is misplaced and represents an expensive diversion from

other potentially more valuable and commercially productive programs. Moreover, the British government, according to the British National Space Centre, has no objections to France funding a major portion of the Ariane 5 and Hermes programs.

## Italy

Italy does not plan to develop and build an air-breathing aerospace vehicle, according to Italian government and industry officials. However, Italy is interested in participating in future European aerospace plane development efforts. According to Italian government and industry officials, Italy cannot afford to build an aerospace vehicle on its own, and such an endeavor would have to be a European effort carried out through the European Space Agency. Although Italy's 5-year (1987 to 1991) National Space Plan does not address the development of an air-breathing aerospace vehicle, the plan does include funding for technological research. Italian Space Agency officials told us that funding under these categories has been used for research on air-breathing aerospace vehicles.

Italy plans to use feasibility studies on air-breathing propulsion as the basis for its participation in possible future European development efforts, according to an Italian Space Agency official.

Italy's aerospace goals and objectives are contained in its National Space Plan. A key objective of the plan is for the Italian government to assist Italy's aerospace industry by conducting research and tests to help it become more competitive and ensure greater Italian industry participation in European Space Agency initiatives. Italy intends to maintain its position as the third largest contributor to the European Space Agency (after France and Germany), since Italian industry receives considerable benefits from European Space Agency contracts. The Italian Space Agency is presently updating the plan, and its officials said that the revised plan will allocate more resources to research in air-breathing propulsion—a prerequisite for a sizeable effort in the next few years.

After conducting several pioneering studies in hypersonics, interest in air-breathing aerospace vehicles in Italy has been slowly but steadily growing. The Italian Space Agency and Aeritalia have decided to concentrate on selected technologies that would position Italy to participate in future international efforts to develop and build a future aerospace vehicle.

The Ferri Project, under discussion between the Italian Space Agency and Aeritalia's Space Systems Group, is a plan for developing the technology needed to support advanced transportation systems. The plan focuses on the development of selected technologies for an air-breathing, single-stage-to-orbit space launch vehicle, including thermal protection and control; advanced structures and materials; guidance, navigation, and control; and tests and computation methods. According to space agency and Aeritalia officials, the primary objective of the Ferri Project will be the acquisition of a manufacturing and testing capability. The space agency planned to include the project and additional funding for aerospace research and development activities in an updated National Space Plan in 1990.

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## The Netherlands

According to the Director of the Netherlands Institute for Aerospace Programs, The Netherlands will never play a leading role in the development of an aerospace vehicle because of the large investment and facilities required. The Netherlands could participate in a future European Space Agency aerospace vehicle program in a minor capacity, if an appropriate program segment could be obtained. However, the Dutch government currently has no plans for such participation.

Although the Dutch are conducting a limited effort in advanced propulsion, advanced materials, structures, and hypersonic aerodynamics, The Netherlands is not conducting a specific technology development program aimed at aerospace vehicle enabling technologies.

The Netherlands' aerospace goals and objectives are to provide funding for the research base, continue its involvement in international space development programs with an emphasis on cooperation with the European Space Agency in space science and technology, and promote the involvement of Dutch industry in aeronautics and space programs.

The Netherlands Institute for Aerospace Programs funds research aimed at industrial applications, partly funds development projects, conducts technology programs, identifies specialized sectors of the European Space Agency market, and promotes involvement of small businesses.

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## Belgium

Belgium does not publish a space policy or aerospace goals and objectives. Although Belgium participates in various European Space Agency programs, it has no intentions of developing an air-breathing aerospace vehicle, according to U.S. Embassy officials in Brussels.

The Belgium government also has no plans to participate in research, development, and testing of an air-breathing space launch vehicle and/or hypersonic cruise airplane, according to U.S. Embassy officials in Brussels. However, the von Karman Institute for Fluid Dynamics, an international nonprofit scientific organization established and operated under the sponsorship and support of the North Atlantic Treaty Organization's Advisory Group for Aerospace Research and Development, carries out experimental studies on reentry vehicles, including Hermes, and develops computational fluid dynamics techniques for hypersonic flows. If European countries, through the European Space Agency, decide to develop an air-breathing space launch vehicle, then Belgium would probably be interested in participating in the effort, according to Belgian industry representatives.

# European Aerospace Vehicle Programs

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European aerospace vehicle programs in France, Germany, and the United Kingdom are primarily concept or system studies. They consist of fundamental research on enabling technologies.

Although not an air-breathing aerospace plane, the European Space Agency's Hermes spaceplane is the most advanced program. Hermes would serve as a technology demonstrator and an intermediate step in developing a future European air-breathing aerospace plane and would provide Europe with a manned space launch capability.

France conducted a low-level, joint government and industry 3-year system and propulsion concept study to assess the requirements for a reusable space launch vehicle with horizontal takeoff and landing capability. The technical evaluation does not represent a commitment by France to develop a spaceplane. A French Task Force on Hypersonic Research provided the French government with recommendations on the direction that French hypersonic plane development should take in the 1990s. The recommendations are to focus and solidify French aerospace industry's efforts into one aerospace plane design.

Germany is conducting research on air-breathing aerospace vehicles under the national Hypersonic Technology Program, whereas German universities are studying technologies needed to develop such an aerospace vehicle under a separate, but complementary, effort. The primary goal is to develop a European two-stage-to-orbit, fully reusable transport vehicle. Saenger II is the reference (baseline) concept.

The United Kingdom conducted a joint government and industry 2-year proof-of-concept study to evaluate the feasibility of the HOTOL single-stage-to-orbit aerospace vehicle. Although the British government eventually withdrew its financial support, industry secured an international partner that will allow the program to continue, at least on an interim basis.

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## European Space Agency's Hermes Spaceplane and Ariane 5 Launch Vehicle

The Hermes spaceplane and the Ariane 5 launch vehicle programs are major European Space Agency space transportation programs. Both were originally French national programs that were subsequently approved by the European Space Agency for funding and development. In 1987 the European Space Agency agreed to fund Hermes through the initial development phase and Ariane 5 through its completion. The European Space Agency does not plan to undertake the development of a future air-breathing aerospace vehicle until these programs are completed, according to European Space Agency and French government officials.

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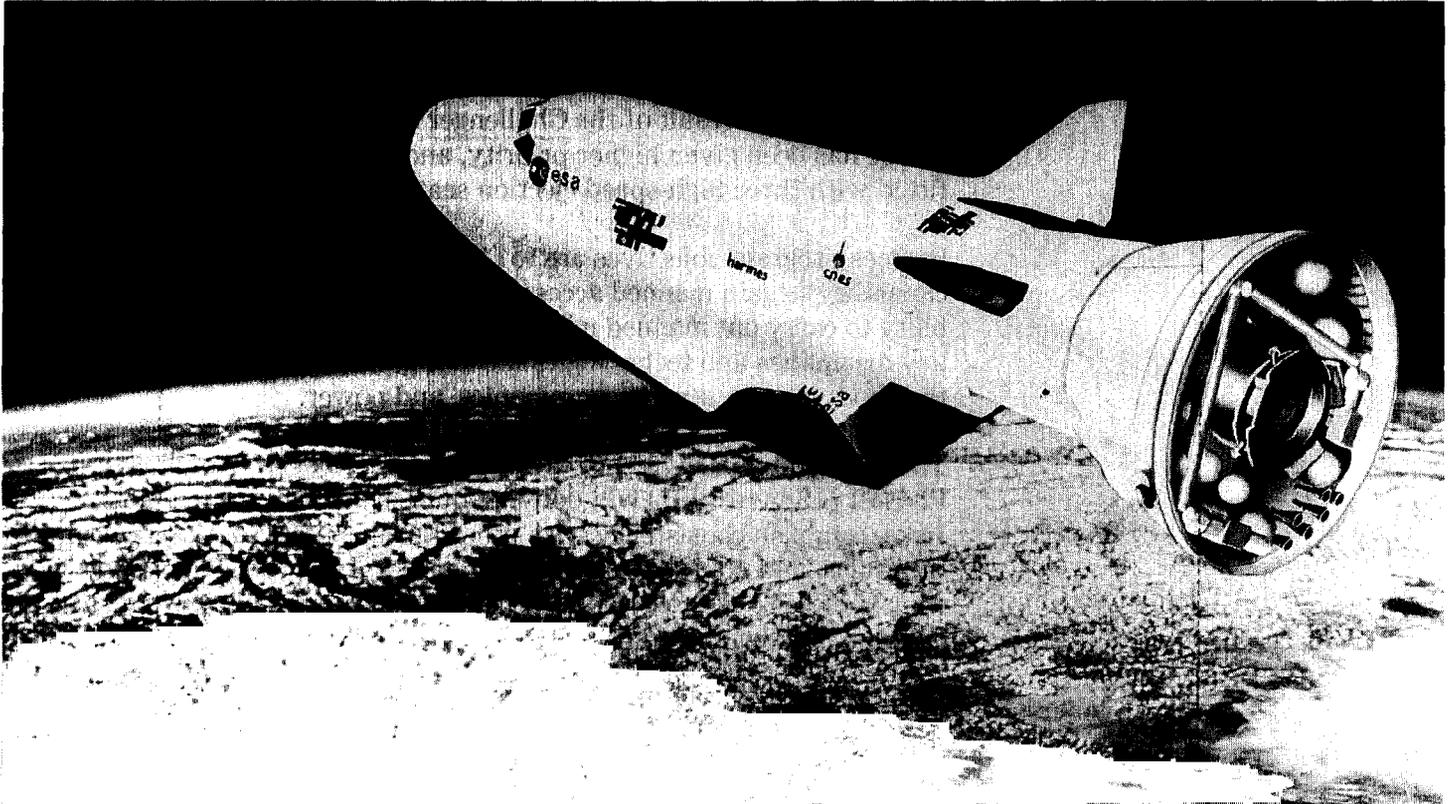
## European Space Agency's Hermes Spaceplane

Hermes is being developed as a manned, reusable, shuttle-like reentry winged vehicle. It would be vertically launched by the Ariane 5 rocket booster from the European Space Agency's Kourou Space Center in French Guiana and would return to earth and land horizontally on a runway.<sup>1</sup> Thruster rockets would be used for maneuvering while in orbit. Figure 3.1 shows the European Space Agency's Hermes spaceplane.

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<sup>1</sup>Hermes could land at any one of several potential dedicated landing sites including Kourou or Cayenne, French Guiana; Brasilia, Brazil; Istres, France; Rota, Spain; Sal, Cape Verde; Dakar, Senegal; Edwards Air Force Base, California; and Cape Canaveral, Florida. These facilities could also serve as launch emergency abort sites.

Figure 3.1: European Space Agency's Hermes Spaceplane



Source: European Space Agency.

Hermes' primary mission is to service the Columbus Free-Flying Laboratory. Other potential missions include providing space transportation for astronauts and supplies to the Columbus pressurized module of the planned U.S. space station, conducting orbital experiments and extravehicular activity, and docking with the Soviet space station Mir. Hermes is also being considered for use both as a space rescue vehicle and the basis for a crew rescue vehicle for the planned U.S. space station.<sup>2</sup>

Hermes is being designed to transport a crew of three and a cargo payload of about 3 tons into low earth orbit. Hermes is not being

<sup>2</sup>Lockheed Corporation contracted with Aerospatiale, Hermes' lead industrial contractor, to provide it with data on Hermes as the basis for a space station rescue system. Lockheed Corporation leads one of two competing U.S. industry teams that are examining concepts for the National Aeronautics and Space Administration for the Assured Crew Rescue Vehicle, which would evacuate space station astronauts in an emergency. Aerospatiale estimates that two Hermes rescue vehicles could cost about \$797 million.

designed to place satellites into orbit. European Space Agency and National Center for Space Studies officials consider unmanned rockets (such as the Ariane launcher) to be more suitable vehicles for that role. Typical missions are expected to last 11 days in space but could last up to 28 days. As a result of the Challenger accident in January 1986, crew safety has been given higher priority, and Hermes is now expected to be fitted with three high-speed ejection seats.

Hermes program objectives are to (1) acquire an autonomous European capability to gain manned access to space, (2) achieve a European capability to carry out manned missions in space, and (3) acquire expertise in key disciplines and technologies including winged vehicle reentry, aerothermodynamics, structures, avionics, and power.

The European Space Agency is developing Hermes in two phases. Phase 1 (1988 to 1991) will define requirements, reduce technology risks, establish consistency with other European Space Agency orbital programs, and plan the next phase. Phase 2 (1991 through 1998) will consist of full-scale development of Hermes. However, according to European government and industry officials, further design changes are likely to delay the program. The first unmanned launch is scheduled for 1998 and the first manned launch for 1999. However, according to a European Space Agency official, the first launch is likely to be rescheduled for sometime after the year 2000. Hermes' operational life is estimated to be about 15 years at a rate of two flights per year.

Program costs, on the basis of an April 1989 estimate, could total more than \$5.7 billion. This figure includes the Preparatory (research) Program (about \$120 million), Development Program (about \$5.1 billion), demonstration costs (about \$308 million), and operation costs (about \$238 million). In November 1987 European Space Agency members approved funding for Phase 1 development totaling \$605 million.

Although similar to the U.S. space shuttle in its aerodynamic design, Hermes would be much smaller but not necessarily less complex. According to the European Space Agency, the smaller size makes it difficult to incorporate in Hermes many of the subsystems found in the U.S. space shuttle. Also, Hermes would not be expected to meet the same demanding launch schedule as the U.S. space shuttle. The spaceplane is not viewed as an alternative space launch system. According to the European Space Agency, Hermes is a necessary precursor to future European spaceplane programs rather than a competitor. European Space Agency officials said that Hermes' value remains unaffected even

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if no future aerospace planes are built, since its main function is to allow European manned access to space.

In addition to an operational role, Hermes would serve as a technology demonstrator for future European aerospace vehicles. A National Office for Aerospace Studies and Research official said Hermes research and development efforts in advanced materials, structures, avionics, computational fluid dynamics, supercomputers, and testing facilities contribute to developing a future air-breathing, single-stage-to-orbit space launch capability.

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### Participation by European Space Agency Members, Industries, and Universities

Hermes is being developed as an optional European Space Agency program with France contributing about 43 percent, Germany 27 percent, and Italy 12 percent. A joint European Space Agency and National Center for Space Studies team is responsible for managing the Hermes program. Other French aerospace companies and research organizations are also participating in the Hermes program under the European Space Agency's industrial policy of just return. For example, Aerospatiale is the prime contractor and Avions Marcel Dassault-Breguet Aviation is the designated contractor for aeronautics (including thermal reentry protection and flight guidance control). The European Propulsion Company is working on thermal protection. The National Office for Aerospace Studies and Research is developing new computational fluid dynamics codes to predict hypersonic flows for Hermes and is conducting reentry and trajectory research.

German organizations and industry are also involved in Hermes research, testing, and development. For example, Dornier is conducting research on Hermes' environmental control and life support systems. Messerschmitt-Boelkow-Blohm is a major subcontractor for propulsion equipment. The German Aerospace Research Establishment is conducting research on Hermes' design configuration and is building the Goettingen High-Enthalpy Tunnel, a Mach 7 free-piston shock tunnel facility to test Hermes' reentry conditions.

Italian aerospace companies, the Italian Aerospace Research Center, and Italian universities are participating in the Hermes program. For example, Aeritalia is involved in the design, development, construction, and testing of the thermal control subsystem and the design and construction of the wing structure and forward fuselage. Aeritalia also plans to conduct work on internal insulation and cryogenic fuel tanks. The Center is coordinating a European Space Agency-sponsored basic

research effort involving 10 Italian universities. This effort includes theoretical and numerical studies in hypersonics involving the Euler, boundary layer, and Navier-Stokes hypersonic regimes and experimental studies in heat transfer from the vehicle's body to the boundary layer by means of infrared thermography.

Belgium's National Corporation for Aerospace Construction has a sub-contract for the composite material structure of Hermes' nose section. In addition, the von Karman Institute for Fluid Dynamics carries out experimental studies in a Mach 14 hypersonic wind tunnel and develops computational fluid dynamics techniques for hypersonic flows.

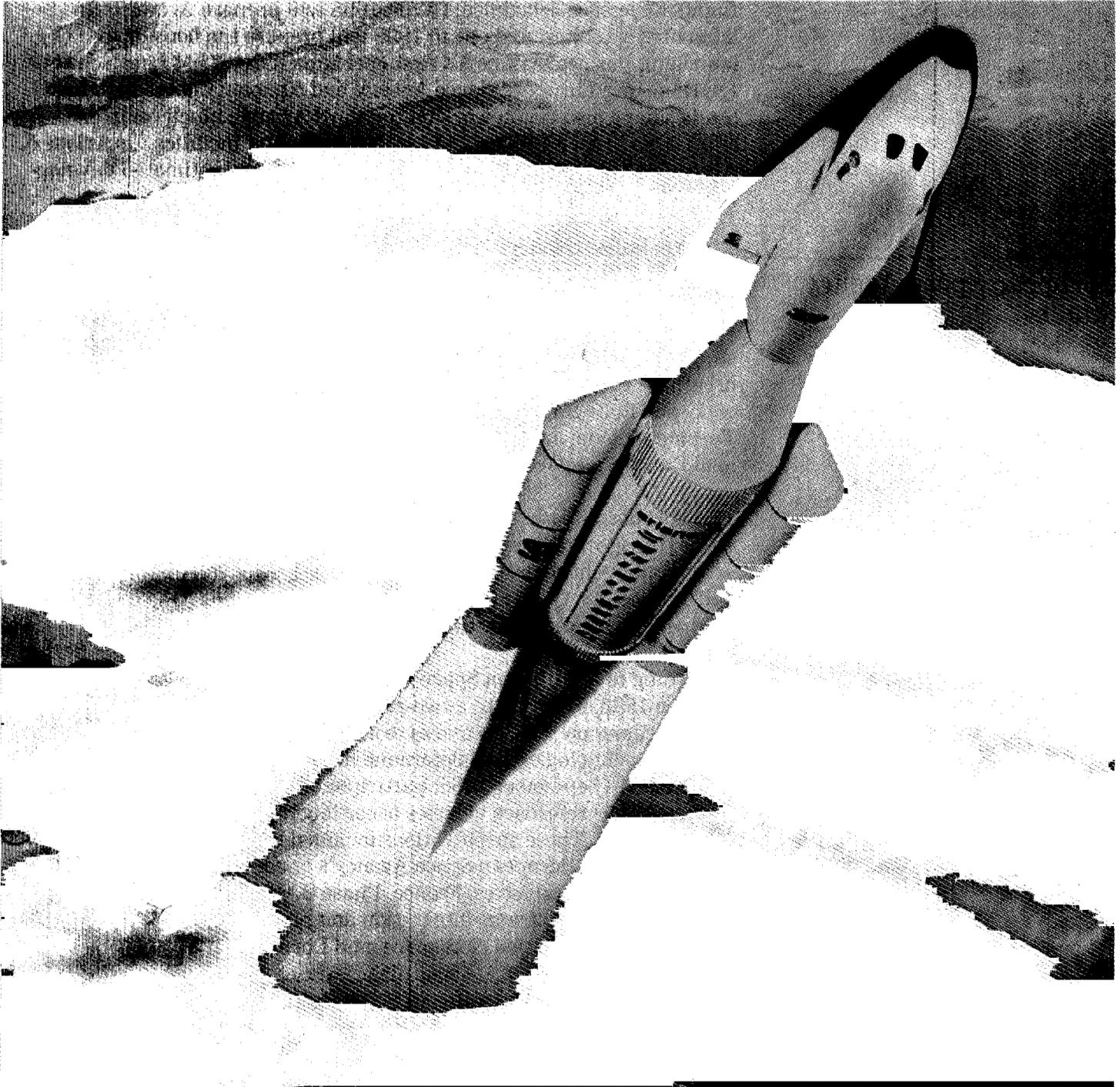
In November 1990 the four prime aerospace companies developing Hermes—Aerospatiale, Avions Marcel Dassault-Breguet Aviation, Deutsche Aerospace, and Aeritalia (now Alenia)—announced the creation of a new management company, Euro-Hermespace, to oversee full-scale development and production. The company is expected to begin operations in mid-1991 in Toulouse, France, as the European Space Agency's prime contractor for the Hermes spaceplane. The two primary owners, Aerospatiale and Avions Marcel Dassault-Breguet Aviation, also plan to create a separate company, Hermespace France, to represent them in the new company.

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### European Space Agency's Ariane 5 Launch Vehicle

Ariane 5, the latest in the series of Ariane rockets, is being developed as a conventional three-stage expendable space launch vehicle designed to launch a total of 15,256 pounds into geostationary transfer orbit. It would be capable of launching navigation and earth observation satellites into low earth orbits, telecommunication satellites into geostationary transfer orbit, space probes for planetary missions, and the Hermes spaceplane. Figure 3.2 shows the Hermes spaceplane being launched from the Kourou Space Center by the Ariane 5 rocket booster.

Figure 3.2: European Space Agency's Ariane 5 and Hermes Spaceplane



Source: European Space Agency.

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Ariane 5 development began in February 1988. Three qualification flights have been scheduled: two in 1995 will prepare Ariane 5 for launching satellites, and one in 1998 will prepare the booster for launching Hermes. Ariane 5's first operational flight has been scheduled for 1996. The European Space Agency and National Center for Space Studies have also begun work on the third Ariane launch complex (ELA-3) in French Guiana and associated ground facilities for Ariane 5. According to the European Space Agency, the total estimated development cost for Ariane 5 as of August 1990 is about \$5 billion.

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## European Space Agency Studies

According to a European Propulsion Company official, the National Company for the Study and Construction of Aviation Engines, European Propulsion Company, and Fiat Aviazione participated in a preliminary study sponsored by the European Space Agency in 1986 on air-breathing vehicles that included turborocket, ramjet, and turboramjet concepts. Rolls-Royce, Messerschmitt-Boelkow-Blohm, Motoren- und Turbinen-Union, and the University of Stuttgart participated in a parallel European Space Agency effort.

The European Space Agency also conducted general studies related to space transportation systems that may eventually become the basis for an optional vehicle program, according to a European Space Research and Technology Center official. One objective was to reduce the cost of Ariane 5 by making it partially reusable.

According to a European Space Research and Technology Center official, the 1986 effort led to a two-phase space transportation study that began in January 1988 to assess technological challenges, identify enabling technologies, and determine how to proceed. During Phase 1, completed in September 1988, participants defined single- and two-stage-to-orbit<sup>3</sup> reference vehicles according to European Space Agency specifications. These specifications included being able to launch from and land at the European Space Agency's Space Center in Kourou, French Guiana, and Istres, France. Phase 2, completed in March 1989, concentrated on airframe integration and propulsion. Messerschmitt-Boelkow-Blohm, British Aerospace, and Dornier were responsible for the

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<sup>3</sup>A single-stage-to-orbit vehicle would take off horizontally from a conventional runway, reach hypersonic speeds, attain low earth orbit, and return to land on a conventional runway. A two-stage-to-orbit vehicle would consist of an air-breathing first stage, which would take off and land from a conventional runway, and a rocket-propelled upper stage, which, at a certain altitude, would separate and continue into orbit. The second stage, a reentry winged vehicle, would glide back to earth and land on a conventional runway. A two-stage-to-orbit vehicle could also consist of a heavy-lift transport aircraft first stage and a rocket-propelled second stage.

airframe portion of the study, and Rolls-Royce, Motoren- und Turbinen-Union, and Fiat Aviazione conducted the propulsion portion of the study.

## France's National Center for Space Studies Systems Study

In 1986 the National Center for Space Studies initiated a 3-year (1986 to 1988) system and propulsion concept study to assess the requirements for a reusable space launch vehicle with horizontal takeoff and landing capabilities. The Center evaluated several different vehicle concepts and missions and innovative propulsion systems. Its objectives were to reduce launch costs and constraints, including alternatives to the European Space Agency launch site in French Guiana.

Center officials described the study as a technical evaluation and said the study does not represent a commitment by France to develop a spaceplane. According to the Center's Division Chief for Future Projects, the French government's commitment to Hermes does not enable it to invest in other large technology programs. The official also said that the Center has not decided whether to enter into a technology development program.

The study was a joint effort between the French government and industry, with the Center providing most of the funding. Aerospatiale and Avions Marcel Dassault-Breguet Aviation conducted the systems portion of the study to identify the most promising vehicle concepts for single- and two-stage-to-orbit space launch vehicles. Aerospatiale's participation in the Center's study is known as Systeme de Transport Spatial (STS) 2000, or Space Transportation System 2000. Avions Marcel Dassault-Breguet Aviation's designation for its participation in the Center's study is the Systeme de Transport Aerobie Reutilisable a Decolage et Atterrissage Horizontaux (STAR-H), or Reusable Air-Breathing Transport System-Horizontal Landing. The National Company for the Study and Construction of Aviation Engines, European Propulsion Company, and National Office for Aerospace Studies and Research conducted the propulsion portion of the study to identify the most promising propulsion system concepts. According to an Avions Marcel Dassault-Breguet Aviation official, Aerospatiale completed its evaluation in early 1990, and Avions Marcel Dassault-Breguet Aviation was expected to finish its assessment in November 1990.

Although its primary purpose was to assess future space transportation systems, the study became part of a larger program on hypersonics after the French Ministry of Research and Technology joined the effort in

1989. According to an Avions Marcel Dassault-Breguet Aviation official, the study's technical results are being used as a guide for future French efforts in hypersonics.

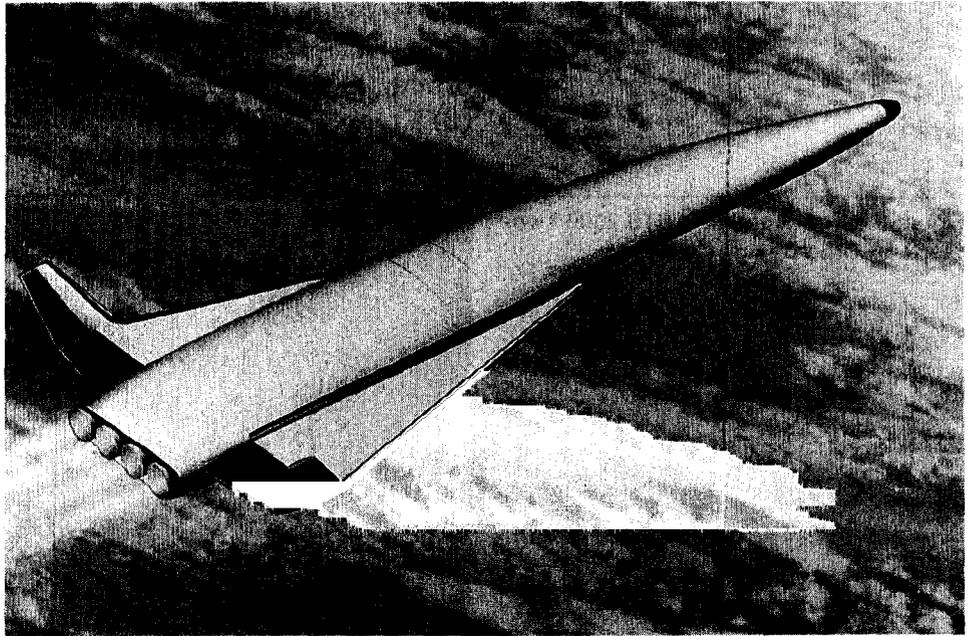
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### Aerospatiale's STS 2000 System Study

The objectives of Aerospatiale's STS 2000 system study were to analyze system architecture requirements, review different concepts, adapt and improve design tools, and develop a technology plan. Developing and building a reusable air-breathing space launch vehicle would require a synergism of several critical technological breakthroughs that include (1) reusable advanced materials able to withstand high temperatures, (2) a combined-cycle air-breathing propulsion system, (3) full integration of the airframe and propulsion system, and (4) use of computational fluid dynamics to simulate airflows, temperatures, and pressure contours around various design configurations.

The STS 2000 study considered both single- and two-stage-to-orbit spaceplane concepts. Both concepts are designed to takeoff from a conventional runway, deploy a 7-metric ton payload into low earth orbit, and land horizontally. Aerospatiale's single-stage-to-orbit spaceplane concept would combine air-breathing and rocket engines. Vehicle designs include a (1) 338-metric ton air-breathing horizontal takeoff and landing spaceplane 73 meters in length with a wingspan of 27.8 meters (see fig. 3.3) and (2) rocket-propelled vertically launched reentry winged vehicle that would land horizontally.

**Figure 3.3: Aerospatiale's STS 2000  
Single-Stage-to-Orbit Design Concept**



Source: Aerospatiale.

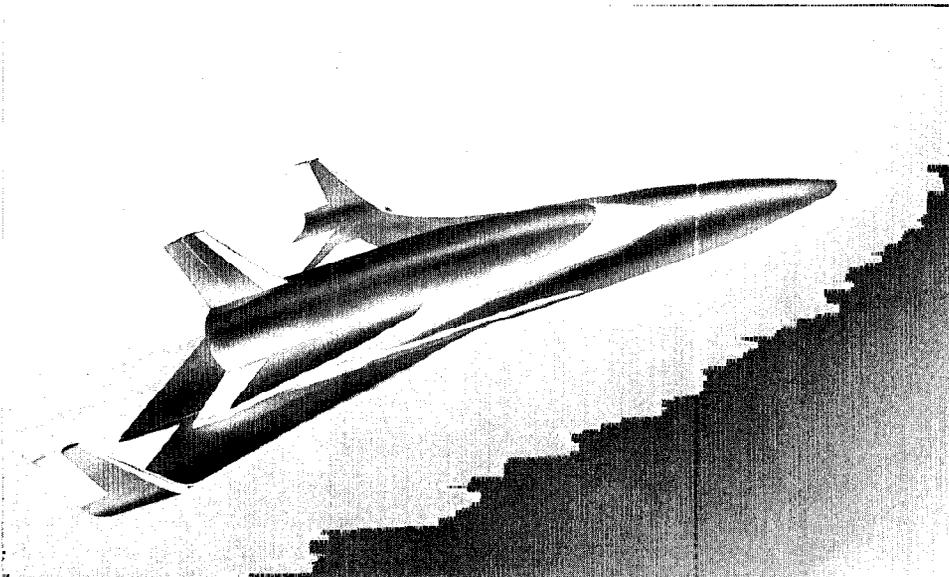
According to the U.S. Air Force Foreign Technology Division, the rocket-powered single-stage-to-orbit vehicle was only used as a comparison to the air-breathing single-stage-to-orbit spaceplane and was not an optimized vehicle design. Propulsion systems that have been considered include an air-augmented rocket, turborocket-rocket, and a turborocket-ramjet-rocket. The latter concept, according to Aerospatiale, currently offers the best performance from Mach 0 to 25 at various altitudes.

According to National Aeronautics and Space Administration officials, Aerospatiale engineers have decided to redirect their work on the STS 2000 spaceplane program to use an air-breathing main or first-stage engine through speeds of Mach 12. This decision will require the use of a scramjet. The officials commented that this is the first time that another country has cited this approach.

Aerospatiale's two-stage-to-orbit spaceplane concept would consist of an air-breathing first-stage accelerator and rocket-propelled second-stage orbiter. Separation of the orbiter from the accelerator would occur at Mach 6 at about 35 kilometers in altitude. The first stage, which would fly from Mach 0 to 6, would land at Kourou, French Guiana. The second stage, which would fly from Mach 6 to 25, would be capable of landing on a conventional runway. Vehicle designs include (1) an 83-metric ton

air-breathing first-stage accelerator 60 meters in length with a wingspan of 31.4 meters and a 121-metric ton rocket-propelled second-stage orbiter 38 meters in length with a wingspan of 16 meters (see fig. 3.4), (2) a rocket-launched recoverable reentry winged vehicle, and (3) a rocket-launched recoverable or semi-reusable winged/ballistic vehicle.

Figure 3.4: Aerospatiale's STS 2000 Two-Stage-to-Orbit Design Concept



Source: Aerospatiale.

### Avions Marcel Dassault-Breguet Aviation's STAR-H System Study

According to an Avions Marcel Dassault-Breguet Aviation official, STAR-H was not an aerospace vehicle program but rather an effort to build a reliable data base on aerodynamics, integration of the engine and airframe, stage separation, structures, and materials for further analysis. Its objective was to identify promising concepts and the most critical technologies for future space transportation systems. STAR-H was conducted in two phases. Phase 1, a 1-year study (1987 to 1988), analyzed the most critical technologies for a two-stage-to-orbit vehicle with an air-breathing first stage. According to a company official, the basic concept retains a version of Hermes as the second stage and replaces Ariane 5 with a recoverable first stage booster. The first stage, derived

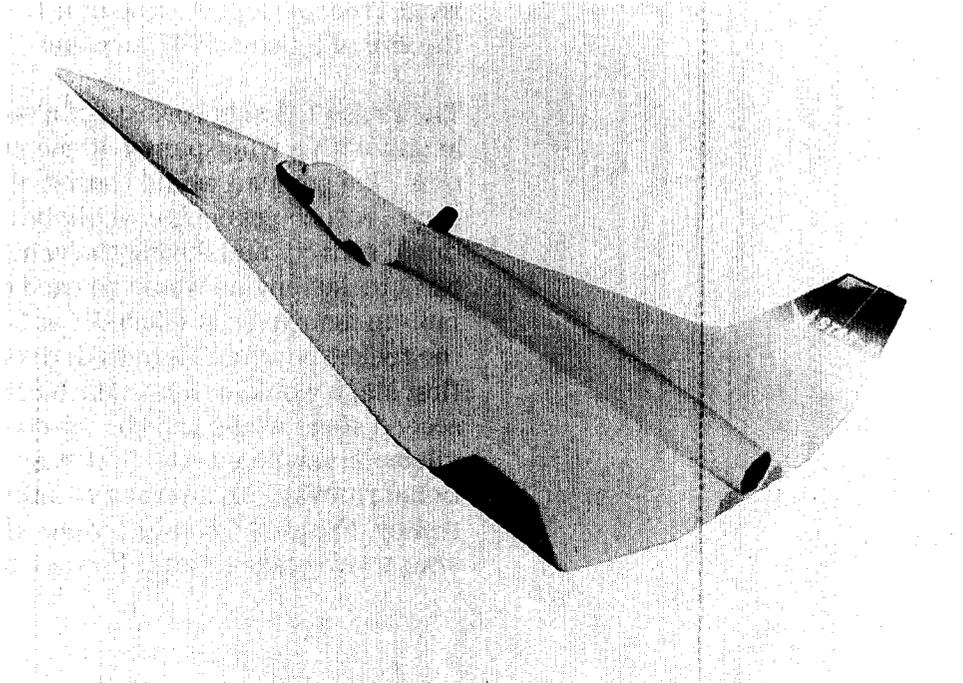
from Transporteur Aerospatial 1, or Aerospace Transporter 1,<sup>4</sup> would be the size of a Boeing 747 airplane.

The Phase 1 design consists of a two-stage-to-orbit vehicle 80 meters in length with a wingspan of 40 meters and a takeoff weight of 400 metric tons. The payload would consist of 3 passengers and 3 metric tons of cargo. A turbojet engine would be used during takeoff from a conventional runway and during the vehicle's acceleration and climb. A turborocket engine would be used during supersonic cruise and for a pull-up maneuver at Mach 6.1 at 25 kilometers in altitude. Separation of the rocket-powered Hermes-derived second stage from the air-breathing first stage would occur at Mach 5.45 at an altitude of 41 kilometers. The second stage would then be injected into orbit at an altitude of about 110 kilometers, whereas the first stage would return to land on a conventional runway. An alternative launch concept involves a rocket-powered trolley. Figure 3.5 shows Avions Marcel Dassault-Breguet Aviation's STAR-H two-stage-to-orbit Phase 1 design concept.

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<sup>4</sup>Transporteur Aerospatial 1 was a 1964 Avions Marcel Dassault-Breguet Aviation concept study of a two-stage-to-orbit transport with an expendable hydrogen/oxygen booster. The vehicle's first stage would have a length of 50 meters, a wingspan of 23 meters, and a takeoff weight of 150 tons. The payload would consist of two passengers and 1 ton of cargo. The first stage would be powered by a kerosene-fueled turbojet, and the second stage would be powered by a hydrogen/oxygen-fueled rocket. Transporteur Aerospatial 1 was followed in 1966 by Transporteur Aerospatial 2, another study that resulted in a larger two-stage-to-orbit vehicle concept.

**Figure 3.5: Avions Marcel Dassault-Breguet Aviation's STAR-H Phase 1 Design Concept**



Source: GAO.

Phase 1 also included the identification of critical technologies. In October 1988 Avions Marcel Dassault-Breguet Aviation presented the National Center for Space Studies with a list of critical technologies it had identified (including advanced propulsion, airframe structures, and integration of the propulsion system with the airframe) and a research and development plan for Phase 2.

Phase 2 (1988 to 1992) involves a more detailed analysis of critical aspects of the basic concept and preliminary analyses of alternate concepts.

Avions Marcel Dassault-Breguet Aviation envisions a flight demonstrator by the year 2000 and final system completion by 2005. The National Company for the Study and Construction of Aviation Engines and European Propulsion Company are conducting research on the turborocket propulsion system and, according to an Avions Marcel Dassault-Breguet Aviation official, could have the engine developed by 1996. The European Propulsion Company plans to use Sepcarbinox for the engine's blades, turbine blisk (a turbine disk with integral blades),

and nozzle; Cerasep in the flame holder; and metal matrix composites for the combustor chamber.

Adoption of a final STAR-H program (beyond Phase 2) depends on the availability of European Space Agency funding and identification of a mission for such a vehicle. According to an Avions Marcel Dassault-Breguet Aviation official, French government support may be difficult to obtain because the program will not result in a final product or have an immediate payoff. The official also said the STAR-H project would serve as a building block in developing an aerospace vehicle if the French government decides to develop and build a spaceplane after Hermes becomes operational.

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### **National Center for Space Studies Propulsion Study**

The National Company for the Study and Construction of Aviation Engines, European Propulsion Company, and National Office for Aerospace Studies and Research are conducting the propulsion portion of the National Center for Space Studies system study to identify the most promising concepts for propulsion systems. The European Propulsion Company is conducting research on advanced rocket engines. In addition, the three organizations have formed a team to evaluate combined engine concepts. Each one brings its particular area of expertise to the study. For example, the National Company for the Study and Construction of Aviation Engines has expertise in air-breathing engines, the European Propulsion Company in rockets, and the National Office for Aerospace Studies and Research in aerospace research. The National Center for Space Studies propulsion study is discussed further in chapter 4.

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### **French Task Force on Hypersonic Research**

The French Ministry of Research and Technology announced in November 1989 that it was investing about \$2.4 million to coordinate the hypersonic research efforts being undertaken by Aerospatiale, Avions Marcel Dassault-Breguet Aviation, National Company for the Study and Construction of Aviation Engines, European Propulsion Company, and National Office for Aerospace Studies and Research. The French Ministry of Defense asked French industry, in connection with the National Office for Aerospace Studies and Research, to establish a task force and prepare a report on hypersonic technologies that would serve as a guide for future French government investment in hypersonics.

In May 1990 the French Task Force on Hypersonic Research provided the French government with recommendations on the direction that French hypersonic plane development should take in the 1990s. According to a Ministry of Research and Technology official, the effort is to focus and solidify French aerospace industry's efforts into one aerospace plane design. If implemented, the plan could establish an executive agency within the Ministry of Defense to carry out hypersonic research and development in France. The Ministry of Defense report, which was due in October 1990, is expected to ask the companies to work together on a coordinated design. Once a unified French hypersonics program is initiated, according to the Ministry official, France may seek European cooperation in developing and building a spaceplane.

## Germany's Hypersonic Technology Program

Germany is conducting research for future air-breathing aerospace vehicles under two parallel efforts. Under the Hypersonic Technology Program, government and industry are studying enabling technologies and plan to propose a vehicle concept to the European Space Agency for future European development. Under the Special Research Field Project, universities are working with the German Aerospace Research Establishment to study technologies needed to develop such an aerospace vehicle.

In 1988 the Federal Ministry for Research and Technology initiated the Hypersonic Technology Program, which sets goals and objectives for conducting research and tests and for developing an air-breathing aerospace vehicle as a European effort. The primary goal is to develop a two-stage-to-orbit, fully reusable transport vehicle.

The program is to be implemented in three phases and is expected to be completed in 2005. Phase I is a German national effort in which government and industry are conducting research on a vehicle concept. Phase I consists of conceptual studies and the development of technologies needed for an air-breathing aerospace vehicle. Specific tasks include building and/or modernizing necessary test facilities and testing propulsion components. This phase is expected to last until 1992. At the end of Phase I, Germany's vehicle concept is to be proposed to the European Space Agency for European development under Phases II and III.

Phase II will include the development of a flight demonstrator to validate the technologies developed in Phase I and is estimated to last from

about 1993 to 2000. Phase III will involve flight testing and is estimated to last from about 2001 to 2005.

Principal aerospace vehicle programs under Germany's Hypersonic Technology Program are discussed below. Although not part of the program, additional German industry low-level conceptual studies on several alternative two-stage-to-orbit space launch vehicle concepts are discussed in appendix I.

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### Messerschmitt-Boelkow-Blohm's Saenger II Advanced European Space Transportation System

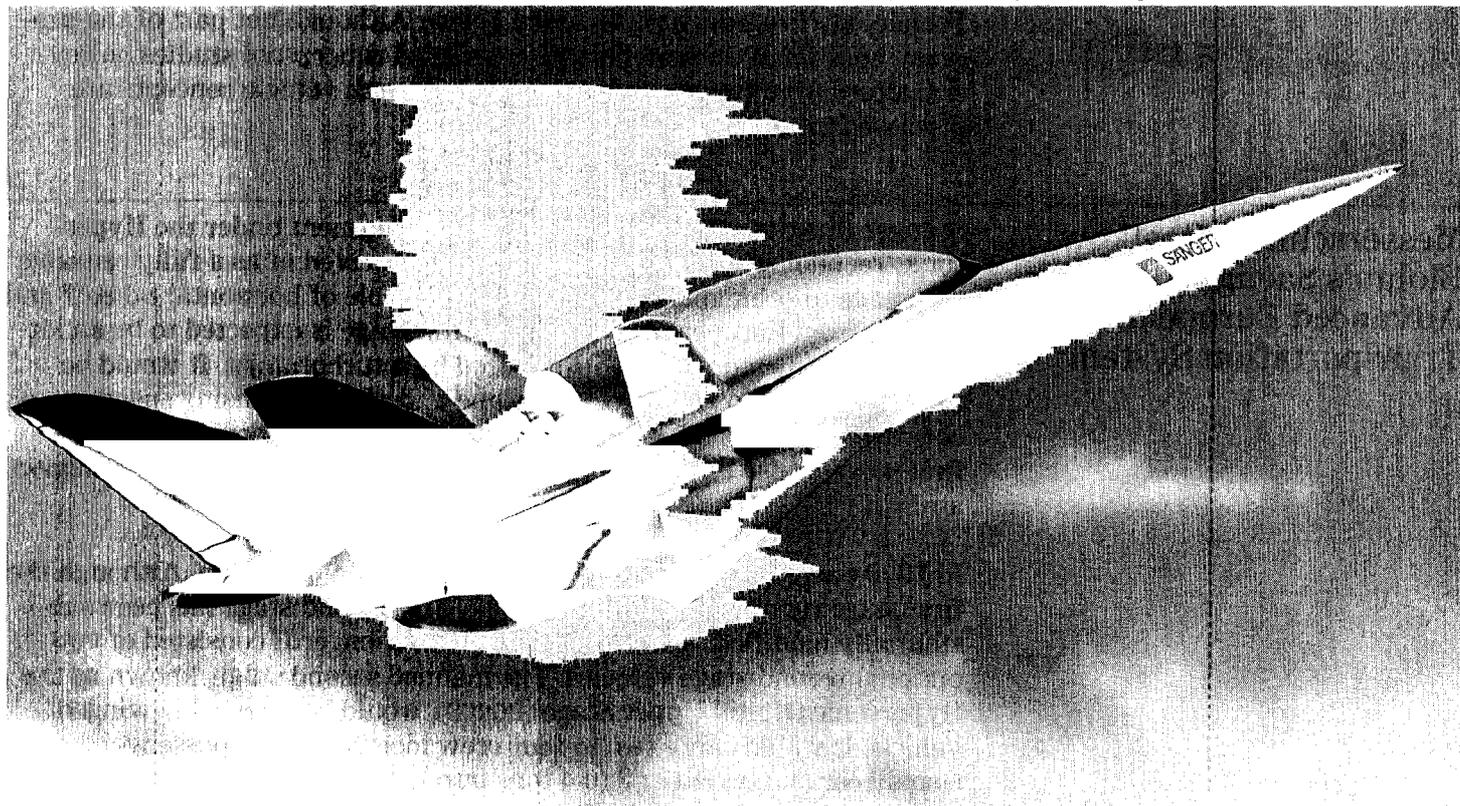
Saenger II is the reference concept for development under the Hypersonic Technology Program. Saenger II is conceived of as a fully reusable two-stage-to-orbit space launch vehicle capable of horizontal takeoff and landing from European airports. The first stage is expected to be an air-breathing hypersonic aircraft powered by a turboramjet. It would be about the size of a Boeing 747 airplane and reach a cruising speed between Mach 4 and 5 and an acceleration speed of about Mach 6.8. The first stage is also envisioned as the basis for future hypersonic transport aircraft.

In 1990 Saenger II underwent a significant design revision. Although the first stage remains unchanged, Saenger II's second stage has been substantially modified. The earlier version of Saenger II consisted of two optional second-stage vehicles. The manned second stage, known as the Hypersonic Orbital Upper Stage (HORUS), would be a reusable winged vehicle. It would carry two to four crew members, four passengers, and a small cargo payload of 2 to 4 tons into low earth orbit. The unmanned second stage, known as the Cargo Upper Stage (CARGUS), would be an expendable vehicle that would launch payloads of up to 15 tons into low earth orbit or 2.5 tons into geostationary orbit. Both second stages would use lightweight, high-performance rocket engines.

Messerschmitt-Boelkow-Blohm has now abandoned the CARGUS second-stage design, primarily for economic reasons, in favor of a lighter, more aerodynamic, and reusable unmanned version of HORUS with a cargo bay. According to a Messerschmitt-Boelkow-Blohm official, designing two different second stages would be too difficult. Also, the aerodynamic drag on the earlier expendable second stage meant Saenger II's first stage would require more thrust. With these changes, Saenger II has a single design for the manned (HORUS-M) and unmanned (HORUS-C) second stage. According to Messerschmitt-Boelkow-Blohm, although the payload capacity has been reduced from 15 to 7 tons, Saenger II with HORUS-C would now have the ability to retrieve satellites or microgravity

experiments in space. Figure 3.6 shows Messerschmitt-Boelkow-Blohm's Saenger II.

**Figure 3.6: Messerschmitt-Boelkow-Blohm's Saenger II Advanced European Space Transportation System**



Source: Messerschmitt-Boelkow-Blohm.

According to an official of Messerschmitt-Boelkow-Blohm's Space Communications and Propulsion Systems Division, Saenger II is being developed to reduce transportation costs; use conventional European airports instead of the Kennedy Space Center in Florida and European Space Center in Kourou, French Guiana, as launch sites; and develop basic technologies for the next-generation passenger aircraft. Messerschmitt-Boelkow-Blohm officials view air-breathing propulsion and fully reusable vehicles capable of horizontal takeoff and landing as a means of reducing launch costs.

Germany views Saenger II as a follow-on to Hermes, according to the Federal Ministry for Research and Technology's Director of Aeronautical and Spaceflight Technologies. The Director said a two-stage-to-orbit

vehicle concept using turboramjets is attractive because scramjets are not required. An official of Messerschmitt-Boelkow-Blohm's Space Communications and Propulsion Systems Division stated that Saenger II is the necessary step between the United Kingdom's HOTOL vehicle and the U.S. X-30 experimental flight vehicle. The official also said the next step in propulsion system development should be the turboramjet and not the more technologically challenging scramjet.

As of November 1990, the costs and schedule for Saenger II development had not yet been determined. In October 1988 an official from Dornier told us that Saenger II could probably cost between \$16 billion and \$20 billion. As of October 1990, Messerschmitt-Boelkow-Blohm officials estimated development costs for two Saenger II vehicles at between \$19.5 billion and \$26 billion. Messerschmitt-Boelkow-Blohm officials anticipate the development of a flight demonstrator in the mid-1990s—provided an international consortium consisting of the European Space Agency, European countries, Canada, and Australia can be established to help fund the demonstrator—and a vehicle by 2000 to 2010. A Dornier official stated that air-breathing engine development is too expensive. The official said that an intermediate vehicle having some of the capabilities of Saenger II could be developed by 2005. The official also said that Saenger II development would follow between 2015 and 2020. A Federal Ministry for Research and Technology official stated that development of an operational vehicle is not likely to occur before 2010. The official further stated that Messerschmitt-Boelkow-Blohm's belief that flight testing will take place in the 1990s is optimistic. The official also said some consideration will be given by the Ministry to the development of a vehicle between development of Hermes and Saenger II. However, the official said it is too early to determine whether such a vehicle will be developed.

Messerschmitt-Boelkow-Blohm officials envision building two operational Saenger II vehicles. Operating costs are estimated at about \$30 million per launch at a rate of 12 flights per year for each vehicle. A Messerschmitt-Boelkow-Blohm official said Saenger II would more likely fly an average of 20 times per year; however, the operating costs for this rate had not been recalculated.

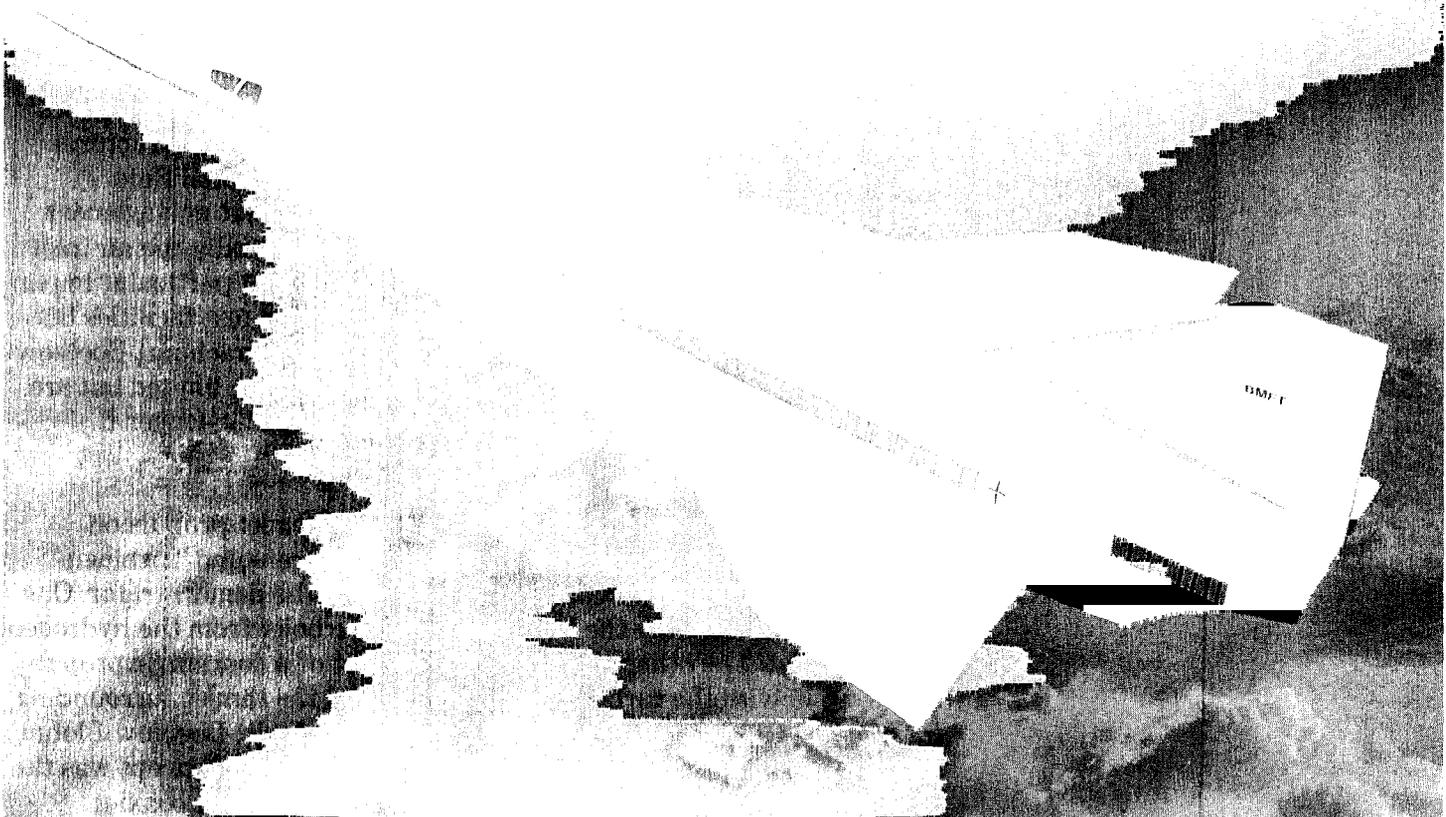
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## Saenger II Subscale Hypersonic Demonstrator Vehicle

The Hypersonic Technology Program also includes the development and testing of a subscale hypersonic flight demonstrator to validate design and propulsion system concepts for Saenger II. The demonstrator aircraft will not be a subscale model of Saenger II but rather an experimental prototype that would represent Saenger II's reusable first stage. The Hypersonic Technology Experimental (HYTEX) vehicle (see fig. 3.7) would have an overall length of about 75 feet, height of about 20 feet, wingspan of about 30 feet, and takeoff weight of approximately 18 tons. It would be able to reach a speed of about Mach 5.6 for a 1-minute flight test of a Saenger II-type first-stage engine. Development of the demonstrator by Messerschmitt-Boelkow-Blohm is expected to begin in 1993, and its first flight is scheduled for 1998, provided that international partners can be found. According to Messerschmitt-Boelkow-Blohm's Director of Advanced Space Transportation Systems, as of November 1990, HYTEX development costs between 1993 and 1998 could total as much as \$2 billion. However, according to German government and industry officials, as of May 1991, the flight demonstrator's development costs would total more than \$2.9 billion.

As of November 1990, about 30 people were involved in HYTEX configuration work. Personnel from Messerschmitt-Boelkow-Blohm, Motoren- und Turbinen-Union, and Dornier also supported this work. A total of about 60 to 70 people are involved in the HYTEX effort, including the technology program.

Figure 3.7: Messerschmitt-Boelkow-Blohm's Hypersonic Technology Experimental Vehicle



Source: Messerschmitt-Boelkow-Blohm.

Messerschmitt-Boelkow-Blohm's Military Aircraft Division has conducted the initial work on the demonstrator and received a contract from the German government in 1990 to continue its efforts. The work is being coordinated with Dornier and Motoren- und Turbinen-Union, the two other companies that, together with Messerschmitt-Boelkow-Blohm and Telefunken Systemtechnik, comprise the Deutsche Aerospace group. However, according to German officials, the manufacture and test of a subscale demonstrator would require an international effort. Aeritalia is exploring with Messerschmitt-Boelkow-Blohm the technical feasibility of producing and flying the hypersonic demonstrator. According to Messerschmitt-Boelkow-Blohm's Director of Advanced Space Transportation, contacts have also been made with several U.S. companies,

including McDonnell Douglas Corporation, Rockwell International Corporation, and United Technologies Corporation, to discuss building the demonstrator, since Saenger II program officials are concerned that insufficient support for the spaceplane may be forthcoming in Europe.

Messerschmitt-Boelkow-Blohm officials consider the demonstrator critical for verifying advanced technology as well as the prediction codes and methods used for advanced aerothermodynamics and structural design. The demonstrator would also verify computational fluid dynamics codes and methods for flight control and heat management subsystems. Integrating the propulsion system (especially the air inlet and variable expansion nozzle) with the airframe is of particular importance, since some tasks cannot be verified by ground test facilities but only by realistic flight conditions. According to Messerschmitt-Boelkow-Blohm, HYTEX design, fabrication, and flight testing are limited but are important technical goals for achieving an operational Saenger II system.

The demonstrator would be powered by a turboramjet propulsion system. Messerschmitt-Boelkow-Blohm and Motoren- und Turbinen-Union were studying two concepts to be used in the demonstrator. One concept would separate the kerosene-fueled turbojet from the hydrogen-fueled ramjet. The other concept would consist of a concentric propulsion system with the turbojet in the middle and the ramjet surrounding it (a coaxial turboramjet). According to Messerschmitt-Boelkow-Blohm and Motoren- und Turbinen-Union officials, the second concept was the favored technical solution and, since April 1990, only the coaxial turboramjet has been pursued.

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## Subscale Spaceplane

Fallkoerpererprobung (FALKE), or Flight Model Drop Test, is a program funded by the Federal Ministry for Research and Technology and German Aerospace Research Establishment to collect aerodynamic measurements for future European reentry vehicles (such as Hermes) and future supersonic airplanes. German engineers also hope to gather information from the program that would be useful in designing Saenger II. The first drop test of the FALKE unmanned European subscale spaceplane was successfully conducted in September 1990 at a balloon-launching facility operated by the French space agency at Aire-sur-l'Adour, near Toulouse, France. The model spaceplane was lifted by a stratospheric balloon into the upper atmosphere, dropped, and guided by remote control to a landing. The flight, which tested the maneuverability of a shuttle-like vehicle, lasted about 6 minutes before the

vehicle's parachutes opened. Two flight tests are planned for a FALKE model of the shuttle and three for a FALKE model of Hermes. The FALKE vehicle was built by Opto-Elektronik und Hydraulik, Raumfahrt und Umwelttechnik, or Opto-Electronic and Hydraulic, Space Flight and Environmental Technics, commonly referred to as OHB System of Bremen, Germany.

The FALKE flight tests are intended to test the aerodynamic characteristics of the European Space Agency's Hermes spaceplane in the transonic and supersonic ranges. According to an OHB System official, actual flight tests provide aerodynamic data that cannot be obtained from wind tunnel tests.

Once FALKE has reached an altitude of about 25 miles, the vehicle is released from the balloon to accelerate in a free-fall until it reaches its maximum speed of approximately Mach 1.7 at an altitude of about 18.6 miles. Measurements are completed at an altitude of approximately 3.1 miles at which point a three-stage parachute system is activated. The vehicle is 23 feet in length and 1,323 pounds in weight.

OHB System is proposing to follow up the missions of FALKE's shuttle version with the production and flight testing of a 1 to 2.5-scale version of the Hermes spaceplane to verify its aerodynamic design for the reentry phase. To date, the only aerodynamic data available for Hermes are from computational fluid dynamics simulations and wind tunnel tests using models. If approved, the larger model would be used in three flight tests in 1992 to 1993. According to OHB System's Managing Director, the Hermes version of FALKE is expected to cost about \$6.6 million, including the cost of a flight test. A European Space Agency and National Center for Space Studies team is planning to review FALKE's first test results before agreeing to fund a Hermes version of the subscale spaceplane.

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### Special Research Field Project

The German Research Association and state ministries are funding a Special Research Field Project in which some German universities (designated "centers of excellence") and the German Aerospace Research Establishment are studying technologies critical to the development of an aerospace vehicle. This work complements the Hypersonic Technology Program, according to a University of Stuttgart official. The official also said that the entire program is expected to last about 15 years with contracts awarded annually to individual universities. The German

Research Association has already approved most of the special hypersonic research projects. For example, contracts were to be awarded to the Rheinland-Westfalia Technical University of Aachen to study propulsion technologies and conduct configuration studies and to the University of Stuttgart to study different types of advanced materials and propulsion. Other universities involved in hypersonic research include the Technical University of Braunschweig (structures), the Technical University of Munich (systems and design), and the Universität Bundeswehr, or University of the Armed Forces, in Munich.

National Aeronautics and Space Administration officials said the significant university involvement in Germany (and in Europe) with aerospace plane programs is a sharp contrast to U.S. university involvement in the NASP Program. The officials said the net result will be a significant increase in the number of trained hypersonic personnel in Europe.

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## United Kingdom's British National Space Centre Concept Study

In mid-1985 the British National Space Centre approved a 2-year (1985 to 1986) study to evaluate the feasibility of a concept proposed by British Aerospace and Rolls-Royce for the HOTOL single-stage-to-orbit aerospace vehicle. In July 1988 the British government withdrew its financial support from this effort. Rolls-Royce ended its work on HOTOL in 1989. However, British Aerospace is continuing its efforts.

The objectives of the study were to (1) identify technology areas that may be critical to vehicle development and propose programs to investigate these areas; (2) demonstrate the feasibility of engine development; (3) show that the vehicle can be engineered at a reasonable cost; (4) identify needed test facilities; and (5) define development costs. The study included the examination of several propulsion concepts.

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## British Aerospace HOTOL

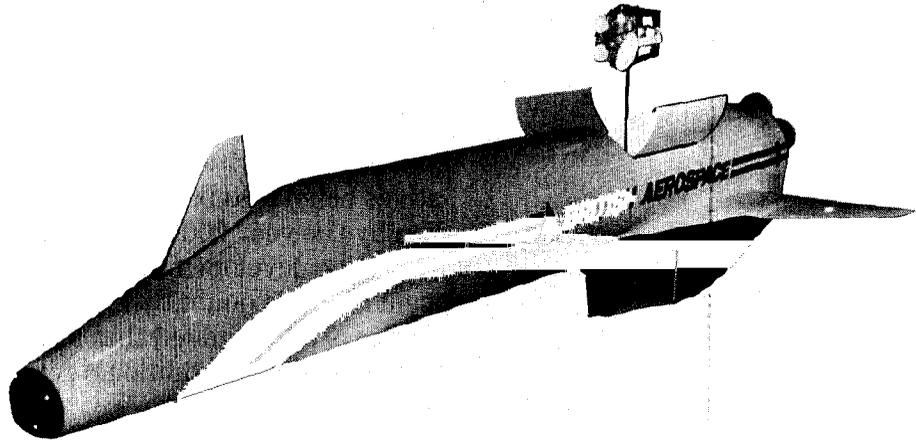
HOTOL is being designed as an unmanned, single-stage-to-orbit, fully recoverable, and reusable space launch vehicle. HOTOL is being designed to carry a single payload of about 7 metric tons into low earth orbit. It would be launched by a laser-guided, rocket-powered wheeled-trolley or rail-borne sledge system from a conventional runway. Thus, the need for heavy-duty landing gear to support the heavy takeoff weight of HOTOL would be eliminated, since the undercarriage would only be deployed on landing.<sup>5</sup> HOTOL would weigh about 275 metric tons (about the size of the

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<sup>5</sup>The 5-to-1 ratio in HOTOL's mass between launch and recovery means that an undercarriage designed for takeoff could effectively absorb the payload fraction of the vehicle.

Concorde airplane) at takeoff, according to a British National Space Centre official. Figure 3.8 shows British Aerospace's HOTOL vehicle concept.

Figure 3.8: British Aerospace's HOTOL Vehicle



Source: GAO.

HOTOL would be powered by Rolls-Royce's RB-545 (Swallow) engine, a combined air-breathing and rocket propulsion engine. The engine, which was classified secret by the British Ministry of Defence, would use atmospheric oxygen in the same way as an airplane's jet engine at low altitudes and switch to HOTOL's on-board liquid oxygen supply at Mach 5 at about 85,000 feet in altitude to boost the spaceplane into orbit. It would glide back to earth and land horizontally on a conventional runway. According to a British National Space Centre official, 5 to 10 years after the unmanned version of HOTOL is developed, manned operations could be achieved by placing a six-passenger capsule in the payload bay.

Automatic pilot and flight control technology is already available for use on HOTOL. This technology is capable of carrying out all stages of operations from takeoff to orbital maneuvering, reentry, and landing.

According to British Aerospace, HOTOL would provide Europe with a low-cost, reliable, independent launch capability. According to British National Space Centre officials, the primary objective of HOTOL is to reduce launch costs by at least five times compared to launch costs of the U.S. space shuttle. HOTOL missions could include launching and recovering satellites and transferring cargo to the Columbus module of the planned U.S. space station. According to a Centre official, HOTOL could accommodate about 8 percent of the world's satellites, since it could launch one satellite weighing up to 7 metric tons. Mission duration would last anywhere from 12 to 100 hours, with the typical mission lasting 24 hours.

According to British National Space Centre officials, industry representatives believe HOTOL could be developed for an estimated cost of \$9 billion by the year 2000, whereas government officials believe HOTOL cannot be developed for that amount or by that date. British government officials doubt that HOTOL could be developed before the year 2005. Centre officials added that accurate cost and schedule estimates cannot be made without additional research.

HOTOL development, which began in 1983, came to a virtual halt in 1988 because the British government elected not to fund further HOTOL research and development. The British government's decision to classify HOTOL's RB-545 engine patent, according to British government and industry officials, has hindered attempts to secure a partnership with the European Space Agency for HOTOL's development. The decision has also hindered British Aerospace efforts to find partners in Europe, which the government has set as a condition for further funding of the program.

British Aerospace officials believe that the RB-545 engine offers advantages over competing propulsion systems being developed in the United States, Germany, and France. British Aerospace has offered HOTOL participation to the European Space Agency and companies in France, Germany, and Italy. Thus far, none has agreed to participate in HOTOL's development, since the potential partners have been denied access to its engine design.

The British Ministry of Defence classified the engine's design soon after the patent application was made because unauthorized release of the technology would pose a threat to British national security. At that time the engine's classification was not considered a handicap to HOTOL's development. According to the inventor, the secrecy provided additional

time to find international partners. According to a British Aerospace official, the secrecy was viewed at first as a way of preventing the engine from being copied by a competitor. In 1986 the inventor sold HOTOL's engine patent to Rolls-Royce.

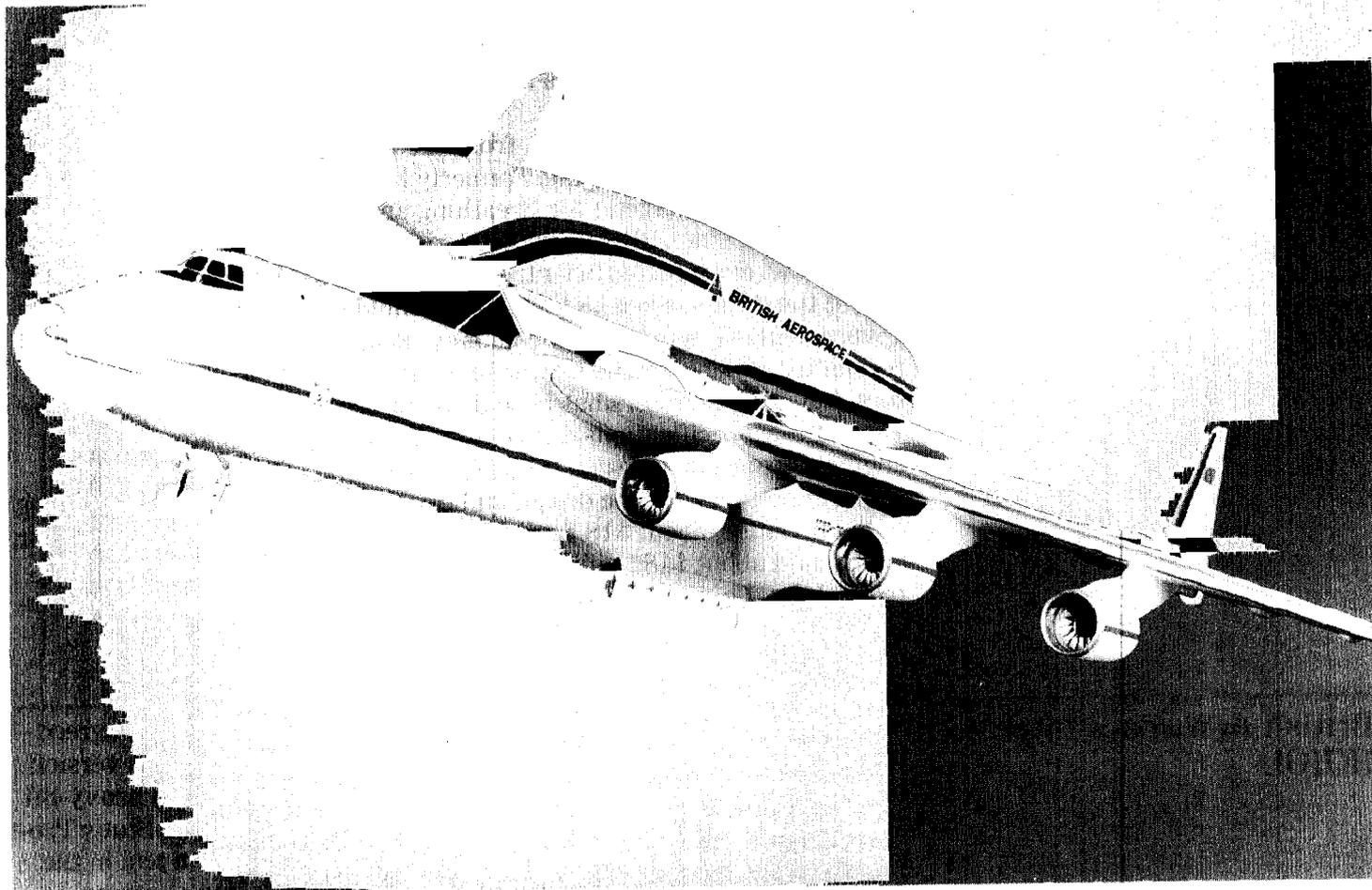
The inventor of HOTOL's engine, frustrated by its classification, has developed a successor engine. Formerly known as Satan, the design has been renamed Synergetic Air Breathing and Rocket Engine. Although similar to the HOTOL RB-545 engine design, this engine is believed to be heavier but more fuel-efficient. The inventor has thus far refused to patent the design, since he fears it too would be classified by the British government. He set up a new company, Reaction Engines, to conduct feasibility studies for the new engine and has begun looking for investors. Enlisting investors has been difficult because, without patent protection, few specifications can be disclosed without threatening the engine's proprietary design. Thus far, he has been unable to raise the capital necessary for the design and proof-of-concept phases. According to the inventor, about \$18.5 million was required initially to develop the engine and about \$185 million will be required to develop the enabling technology. He added that another \$3.2 billion will be necessary to complete the project.

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### British Aerospace Interim HOTOL

British Aerospace and the Soviet Ministry of Aviation Industry agreed in July 1990 to study the feasibility of air-launching an interim version of HOTOL from the back of the Soviet Union's Antonov An-225 heavy-lift transport aircraft, as shown in figure 3.9. The 6-month Joint Study Program was conducted simultaneously in the United Kingdom and in the Soviet Union with each organization sharing the data and analyses.

Figure 3.9: British Aerospace's Interim HOTOL and the Soviet Union's Antonov An-225 Transport Aircraft



Source: British Aerospace.

British and Soviet officials agree that a low-cost reusable space launch vehicle is needed to support long-term manned space stations. According to British Aerospace's Deputy Chief Executive for Engineering, a version of HOTOL launched at an altitude of about 30,000 feet from the An-225 could also provide a low-cost satellite launch system. He estimates that the vehicle would have the capability of placing a 7.7-ton payload into low earth orbit from an equatorial launch site. After deploying its payload, this version of HOTOL would land horizontally on a conventional runway. The An-225 is the largest production aircraft in the world and is designed to carry heavy loads on its back. The An-225 was initially designed to transport the Soviet Buran space shuttle and would be capable of launching the estimated 275-ton orbiter.

British Aerospace and Soviet Ministry of Aviation Industry officials said the RB-545 engine could be replaced on an interim basis by high-performance rocket propulsion, since HOTOL would be launched from an airplane instead of taking off from a runway. According to British Aerospace, Interim HOTOL would provide a useful near-term initial operating capability without requiring the simultaneous development of an advanced airframe structure and an advanced air-breathing engine. Experience gained from such a vehicle, according to British Aerospace, could then be expected to lead to a single-stage-to-orbit HOTOL. The Deputy Minister of the Soviet Ministry of Aviation Industry said that the project is based on a sound concept and that the An-225 can be a moving launch pad for HOTOL.

Under the agreement reached between British Aerospace and the Soviet Ministry of Aviation Industry, the Soviets studied Interim HOTOL's separation from the An-225 and the possibility of developing a high-performance, oxygen-hydrogen rocket engine for the vehicle. The Soviet work, which included wind tunnel testing, also assessed heat protection improvements to the An-225. British Aerospace studied the design and performance requirements for the vehicle, its operation and support, and the economic viability of the air-launch concept.

According to the Director of the Soviet Central Aero-Hydrodynamics Institute, the initial study results, as of October 1990, appeared to be favorable. In April 1991 British and Soviet engineers reported that using the An-225 as the first stage for Interim HOTOL is technically sound. Concerns included Interim HOTOL's weight and stability on top of the An-225, the space launch vehicle's ability to ignite its rocket engines and take off while the An-225 was in flight, and the type of equipment that would be required during high-speed separation of Interim HOTOL from the An-225. This conclusion was reached after 7 months of study and extensive scale-model tests in a wind tunnel at the Soviet Central Aero-Hydrodynamics Institute in Zhukovski near Moscow.

A new agreement must be reached for work to continue on the project, since the initial 6-month Joint Study Program has ended. A British Aerospace official said that, if successful, the results will be presented to the European Space Agency as a Soviet-European project. British and Soviet officials have stated that an operational version of an air-launched HOTOL would be possible about 10 years after collaborative partners are found and funding is secured.

Use of the An-225 may provide British Aerospace with the possibility of designing an Interim HOTOL space launch vehicle capable of meeting some of the original program objectives at lower cost. According to British Aerospace's Deputy Chief Executive for Engineering, the estimated development costs of Interim HOTOL, as of September 1990, totaled about \$4.6 billion, and recurring costs totaled about \$16 million per flight, about one-third of the payload cost per kilogram of Ariane 5.

Use of the An-225 to launch HOTOL would also serve Soviet interests, since the transport aircraft is otherwise underutilized. The Soviets have announced that they are building five An-225s. The Soviets reportedly have been looking for a suitable spacecraft to launch from the An-225 to regain some of their development costs.

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## Future Direction of European Aerospace Vehicle Programs

France's low-level, joint government and industry 3-year system and propulsion concept study to assess the requirements for a reusable space launch vehicle with horizontal takeoff and landing capability does not represent a commitment by France to develop a spaceplane. However, hypersonic research efforts in France are being consolidated. Recommendations by the French Task Force on Hypersonic Research indicate the direction that French aerospace plane development should take in the 1990s and serve as a guide to future investment in hypersonic technologies. The French government wants to focus and solidify French industry's efforts into one aerospace plane design. If the recommendations are implemented, the French Ministry of Defense will have the lead role in carrying out a unified hypersonic research and development program in France.

The first part of Germany's Saenger II System Definition Study under the Hypersonic Technology Program has been completed and confirmed the concept and configuration of the Mach 6.8 first-stage European Hypersonic Transport Vehicle. However, Saenger II's second stage has been significantly redesigned. Although the original concept of different upper stages for manned space operations and for unmanned cargo transportation has been maintained, an unmanned version of HORUS has been found to be a better solution than the original expendable ballistic second stage. Germany is already developing a subscale hypersonic flight demonstrator vehicle to validate Saenger II's design and propulsion system concepts. German engineers are analyzing the results from the first drop test of an unmanned European subscale spaceplane. German universities are heavily involved in hypersonic research. Under

a separate but complementary effort to the Hypersonic Technology Program, the universities are studying technologies needed to develop an aerospace vehicle.

After 8 years of study, the current version of HOTOL represents the best understanding achieved by British Aerospace in designing a cost-effective space launch vehicle capable of delivering a 7- to 10-ton payload into low earth orbit. The most difficult problem in developing such a vehicle is the need to develop the air-breathing engine and airframe simultaneously, rather than in stages. For this reason, British Aerospace, with the Soviet Union, is investigating the development of an air-launched Interim HOTOL. Such a vehicle would prove the airframe design and provide an initial low-cost space launch capability. It would also provide the experience necessary to develop a future air-breathing, single-stage-to-orbit HOTOL.

The results of some of these concept or system studies, the most promising options, and plans for further research were not always available at the time of our review. Nonetheless, the results will help shape the future direction of aerospace vehicle research and technological development in Europe.

According to the U.S. Air Force Foreign Technology Division, fundamental differences exist between the NASP Program and European aerospace vehicle programs. The NASP Program is a technology development and demonstration program to build and test the X-30 experimental flight vehicle. Future operational aerospace planes will be based on the technology developed and demonstrated by the NASP Program.

According to the Foreign Technology Division, with the exception of Germany's HYTEX vehicle (and perhaps, to some extent, the European Space Agency's Hermes spaceplane), European aerospace vehicles are not intended to be technology demonstrators. European programs are directed primarily at developing operational vehicles for specific missions with a minimum of risk. New technologies will not be pursued unless absolutely necessary.

# Development of Enabling Technologies

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The United States, through the NASP Program, is pushing hypersonic technology further than any European country. The United States is ahead of European countries in development of three enabling technologies considered critical for an aerospace plane: air-breathing propulsion, advanced materials, and computational fluid dynamics. Moreover, the United States is the only country that has gone beyond the initial design phases and tested major large-scale components of an air-breathing aerospace vehicle. European aerospace vehicle technology development programs are not as technologically challenging as the NASP Program. However, European countries are making significant progress in the development of enabling technologies, particularly in advanced air-breathing propulsion and advanced materials.

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## The United States Is Pushing Hypersonic Technology the Furthest

The United States is pushing hypersonic technology further than any European country. The Deputy Administrator, National Aeronautics and Space Administration, testified<sup>1</sup> before a joint hearing on the NASP Program in March 1991 that the United States is quite a bit ahead of Europe and Japan in the development of hypersonic technologies due to U.S. levels of investment. In addition, the Director of Defense Research and Engineering, Department of Defense, testified at the same joint hearing that the United States is the pacesetter in all hypersonic technologies and is clearly ahead of its competition.

The NASP Program plans to develop an air-breathing propulsion system for the X-30 that has a higher speed and altitude capability than European systems. The X-30's scramjet is expected to achieve speeds of up to Mach 25 and sustained hypersonic cruise in the atmosphere at altitudes of up to 150,000 feet. In comparison, Saenger II's turboramjet (in the ramjet mode) is expected to achieve speeds of up to Mach 6.6 to 7 and an altitude of about 115,000 feet. HOROL's RB-545 air-breathing engine is expected to achieve speeds of up to Mach 5 (before switching over to rocket propulsion) and altitudes of up to 85,000 feet.

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<sup>1</sup>The testimony was part of a joint hearing on the NASP Program on March 12, 1991, before the Subcommittee on Technology and Competitiveness, House Committee on Science, Space, and Technology, and the Subcommittee on Research and Development, House Committee on Armed Services.

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The X-30 is also expected to be able to withstand the highest temperatures—about 5,000 degrees Fahrenheit<sup>2</sup>—compared to Saenger II's 2,000 degrees Fahrenheit and HOTOL's 2,700 degrees Fahrenheit. NASP's first flight is scheduled for 1997, which is still ahead of HOTOL's first planned flight in 2000 and Saenger II's in 2015. Unlike NASP, no European aerospace vehicle concept includes use of an active cooling system or use of a scramjet—considered by U.S. and foreign government officials and industry representatives as the most advanced and technologically challenging air-breathing engine.

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### U.S. Leads Europe in Testing of Major Aerospace Vehicle Components

The United States is the only country that has gone beyond the initial design phases and tested major subscale air-breathing aerospace plane components. For example, the NASP Program has tested all major components of a subscale scramjet up to speeds of Mach 17 and simulated the airflow within a scramjet up to speeds of Mach 24. However, according to a U.S. expert in hypersonics, the NASP Program has not tested any actual scramjet component at any speed. In fact, the program has not yet designed a scramjet engine component. Rather, the program has conducted only aerodynamic performance-type tests of parts that are geometrically similar to scramjet engines made of heat-sink type materials. As of April 1991, no tests have included the materials and systems (such as cooling, fuel, control, and thermal protection) that an actual engine component must have. Furthermore, only the scramjet module inlet has been tested with partial simulation at speeds of up to Mach 17. The flow within a scramjet has not been simulated at speeds above Mach 8 because no facility currently exists that can actually simulate the flow within a scramjet at speeds above Mach 8. Tests have been made that simulate some portion of the flow within a scramjet at higher speeds. According to the Deputy Program Director of the NASP Joint Program Office, the NASP Program has conducted tests of a subscale scramjet up to Mach 8. It has also conducted tests of scramjet inlets, combustors, and nozzles individually but not together at speeds above Mach 8 and tests of scramjet combustion and airflow at significant levels (at speeds above Mach 24) in shock tunnels.

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<sup>2</sup>According to a U.S. expert in hypersonics, 5,000 degrees Fahrenheit is too high a temperature for most airframe or engine materials to withstand without active cooling. According to the Deputy Program Director of the NASP Joint Program Office, those areas of the X-30 exposed to extreme temperatures of 4,000 to 5,000 degrees Fahrenheit (such as the nose cone; the wing, tail, and engine cowl leading edges; and the inside walls of the engine's combustion chamber), would be actively cooled, even though they will be made of advanced heat-resistant materials.

The United States has also completed wind tunnel testing on one NASP design configuration up to Mach 14. In addition, McDonnell Douglas Corporation has built a full-size (8 by 8 by 4 feet) X-30 fuselage section from silicon carbide-reinforced titanium and manufactured an X-30 fuel tank from a graphite-polyamide composite. Although General Dynamics Corporation has fabricated and tested large, oxidation-coated carbon-carbon composite structures, carbon-carbon composites still lack the strength to be used as structural materials, according to U.S. aerospace industry representatives. In October 1990 the NASP National Program Office selected a single composite design configuration for the X-30 from multiple competing concepts: a lifting body incorporating short wings, twin vertical stabilizers, a two-person dorsal crew compartment, and three to five scramjet engine modules incorporating a small rocket.

Germany, the United Kingdom, and France are in the initial design phases of their air-breathing aerospace vehicle programs. For example, Germany has developed an initial vehicle design for Saenger II and has tested small models of various design configurations in wind tunnels up to Mach 5. The United Kingdom is also still in the initial design phase for HOTOL's configuration and RB-545 engine. France has conducted concept studies but has not reached a design configuration.

## High-Speed Air-Breathing Propulsion

The most critical enabling technology is the propulsion system. For a single-stage-to-orbit aerospace vehicle, a propulsion system must be developed with sufficient thrust and efficiency to power the aerospace vehicle over the full range of speed from takeoff to Mach 25—orbital velocity. Similarly, for a two-stage-to-orbit aerospace vehicle like Saenger II, a propulsion system must be developed to power the vehicle from takeoff to Mach 6 to 7—separation velocity of the rocket-powered second stage from the air-breathing first stage. Currently, the ramjet is the primary propulsion system for aircraft operating at speeds of about Mach 2 to 6.5 and for some missiles. However, the ramjet is inefficient at speeds below Mach 2 and above Mach 6.5.

Hypersonic air-breathing (primarily scramjet) propulsion technology is a Department of Defense high-priority effort in air-breathing propulsion technology. It has the potential, through the NASP Program, to extend military missions to new flight regimes and to provide more cost-effective and on-demand assured access to space. A hypersonic cruise airplane with sustained cruise capability between speeds of Mach 5 and 14

could enhance military capability by carrying out potential military missions such as interdiction, reconnaissance, surveillance, precision targeting and weapons guidance, strategic bombing, and strategic airlift.

According to the Department of Defense, European research and development in the following areas indicate a potential capability for making contributions to meeting U.S. challenges and goals in air-breathing propulsion:

- development and design integration of lightweight, high-temperature, high-strength materials and
- modeling and simulation (including computational fluid dynamics) of complex aerothermodynamic flow and empirically calibrated data bases.

According to the Department of Defense, foreign activity in the development of hydrogen-fueled scramjets is not comparable to the U.S. level of activity in the NASP Program. However, France planned to initiate research on scramjets in 1990.

Formal exchange of information in air-breathing propulsion between the United States and Europe is limited and primarily focused on advanced ramjet propulsion for weapons. The U.S. Air Force has data exchange agreements and memorandums of understanding in materials and testing techniques with various North Atlantic Treaty Organization allies. The United States has close ties with France in ramjet-related and carbon material technologies. According to the Department of Defense, the French are considered world leaders in these areas.

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## France

The propulsion portion of the National Center for Space Studies system study, which involves reviewing engine concepts that combine rocket propulsion with air-breathing propulsion and performing cycle analysis, is being conducted by the National Company for the Study and Construction of Aviation Engines, the European Propulsion Company, and the National Office for Aerospace Studies and Research. According to French industry officials, if the results are promising, a preliminary design analysis would be undertaken to evaluate the propulsion system's weight and key technology requirements. A corresponding technology maturation program would also begin for each concept. Finally, the study would initiate integration of the vehicle and propulsion system performance.

According to the European Propulsion Company's Manager for Advanced Propulsion, the first phase of the combined engine activity was a review of over 100 engine concepts. Initially, three engine concepts were selected for analysis: turborocket, turborocket-ram-rocket, and turboexpander-ram-rocket. Performance analyses have been completed for these concepts and are underway for a turbojet-ramjet, ejector ram-rocket, and liquid air rocket concepts. A European Propulsion Company official said work on the turbojet-ramjet and ejector ram-rocket was expected to be completed in late 1988 and on the liquid air rocket in 1989. The study would not include scramjets initially, since additional funding, engineers, and supercomputers would be required.

The milestones established by the National Company for the Study and Construction of Aviation Engines and the European Propulsion Company include building a demonstrator by 1997, developing a full-scale propulsion system by 2000, and completing the project by 2015. The milestones do not include scramjet technology, which, according to Avions Marcel Dassault-Breguet Aviation officials, could add another 5 years to the program. Officials of the two propulsion companies noted that the National Center for Space Studies is not bound by these milestones.

In 1990 the National Company for the Study and Construction of Aviation Engines and the European Propulsion Company were expected to begin work on cooled turbojets and scramjet engine cycles. Although the two companies have identified the benefits of a scramjet, the technological and funding requirements for scramjet research would use all of their current propulsion resources. Thus, officials of the two companies want to complete current research activities on other engine cycles before beginning scramjet research. They said that a balance is necessary between current efforts and scramjet research.

Although France was not working on scramjets during the time of our visit, it was preparing the necessary steps for scramjet research. According to National Aeronautics and Space Administration official, the National Center for Space Studies system study determined that France should be conducting scramjet research and development. The official said that France, in less than 1 year, had made a major policy shift to begin scramjet work. In addition to the work by the National Company for the Study and Construction of Aviation Engines and the European Propulsion Company on air-breathing combustion, France is developing computational fluid dynamics codes for its efforts in rocket

combustion and is adapting these codes for scramjets. Ten laboratories in France are involved in validating these codes and studying kinetics.

According to officials of the two engine companies, the best scientists and engineers in France are already working on air-breathing and rocket combustion and would not be available to conduct more extensive research on scramjets without adversely affecting ongoing research. France faces a shortage of qualified engineers to work on all propulsion concepts at once. However, if the pool is expanded to include all of Europe, then an appropriate number of engineers may be available, according to French industry representatives.

A European Propulsion Company official said the best propulsion system for a post-Hermes air-breathing aerospace vehicle has not been determined. If a two-stage-to-orbit vehicle is to be developed, then combined-cycle engines would be suitable for the propulsion system. If a single-stage-to-orbit vehicle is to be developed, then a scramjet, liquid air cycle engine, or rocket ramjet propulsion system could be used. The combined-cycle engines would need to be developed regardless, according to the European Propulsion Company official, to provide low-speed propulsion options that could be used to accelerate an aerospace plane from takeoff up to speeds of about Mach 3. The level of effort in France in studying combined-cycle engines is much lower than that of the United States, according to French industry representatives.

In January 1990 the National Company for the Study and Construction of Aviation Engines and the European Propulsion Company created a subsidiary known as Hyperspace to coordinate their propulsion system studies and identify promising new propulsion technologies for hypersonic aircraft. According to the Director of the European Propulsion Company's hypersonic propulsion effort, by 1992 Hyperspace expects to coordinate a French hypersonic propulsion program with annual funding of about \$26 million.

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## Germany

German government and aerospace companies are studying several turboramjet concepts. Under the Hypersonic Technology Program, the Federal Ministry for Research and Technology is proposing several tasks to develop propulsion technologies further. These tasks include development of (1) advanced turbomachinery emphasizing inlet/engine matching and turboengine closure; (2) a ramjet combustion chamber that operates with hydrogen; (3) an aerodynamic model for a variable

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hypersonic intake; (4) elements of a variable nozzle for a hydrogen-operated power plant; and (5) heat transfer elements for air cooling by means of hydrogen and/or hydrogen preheating.

In 1988 the Federal Ministry for Research and Technology contracted with Messerschmitt-Boelkow-Blohm to study ramjet propulsion and with Motoren- und Turbinen-Union to study turbo technology. Messerschmitt-Boelkow-Blohm and Motoren- und Turbinen-Union, the two companies primarily involved in conducting research and development of a turboramjet for Saenger II, are studying several engine concepts. According to a Federal Ministry for Research and Technology official, scramjets are not being studied because they are not required for a two-stage-to-orbit vehicle, such as Saenger II.

In close cooperation with Motoren- und Turbinen-Union, Messerschmitt-Boelkow-Blohm studied four engine concepts: (1) a parallel-installed turbojet-ramjet with a two-dimensional double nozzle, (2) an integrated turbojet-ramjet with a two-dimensional nozzle, (3) an integrated turbofan-ramjet with a two-dimensional nozzle, high-temperature fan, and (4) an integrated turboexpander ramjet with a plug nozzle. In addition, in close cooperation with Messerschmitt-Boelkow-Blohm, Motoren- und Turbinen-Union studied several other engine types including (1) a turboexpander ramjet with liquid hydrogen/liquid oxygen precombustion (air-turboramjet), (2) a turboexpander ramjet with a liquid hydrogen heater, (3) a turboramjet with pre-cooling, and (4) a turbofan-ramjet with pre-cooled core.

According to Federal Ministry for Research and Technology and German industry officials, a coaxial turboramjet was selected in April 1990 as the reference engine concept for Saenger II.

According to an official of Messerschmitt-Boelkow-Blohm's Space Communications and Propulsion Systems Division, Messerschmitt-Boelkow-Blohm's goal to have a 10-ton hydrogen ramjet engine ready for testing in 1992 is on schedule. Messerschmitt-Boelkow-Blohm plans to test a combustion chamber with a small diameter engine before developing a prototype ramjet. Messerschmitt-Boelkow-Blohm then plans to build a 0.5- to 1-meter diameter ramjet and conduct research on combining the turbojet and ramjet concepts.

Other German organizations involved in propulsion research include the German Aerospace Research Establishment, which is studying engine

components, hydrogen/air combustion, and flow processes at high temperatures; the Technical University of Munich, which plans to study propulsion systems; and the University of Stuttgart, which plans to study the problems of hypersonic propulsion.

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## United Kingdom

British industry conducted research on propulsion technologies under the 2-year HOTOL proof-of-concept study. For example, Rolls-Royce conducted rig testing of critical components of the RB-545 engine and engineering studies on propulsion integration.

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## Italy

The Italian Space Agency funded Phase I of a feasibility study on air-breathing propulsion in 1988 and planned to fund Phase II in 1989 to continue research efforts in propulsion, structures, and computational fluid dynamics. These studies will include an analysis of existing facilities and design elements needed for conducting air-breathing propulsion research and identifying the needs of future aerospace vehicle development.

Italy plans to use the study's results as a basis for Italian participation in possible future European efforts to develop an air-breathing aerospace vehicle. In addition, according to the Secretary General of the Italian Aerospace Industries Association, the Italian government and industry recognize the need to undertake a study of a spaceplane project so that the results could be used as an avenue for Italian participation in a possible future European effort to build both a commercial hypersonic transport and a spaceplane.

Fiat Aviazione conducted the first phase of the 1988 feasibility study on air-breathing propulsion for the Italian Space Agency. Research topics included turbines, thermodynamics, combustion in ramjets and scramjets between speeds of Mach 5 and 10, and transonic and supersonic airflows in nozzles. Combustion research was limited because of a lack of test facilities. According to a space agency official, Fiat Aviazione was selected to conduct the study because it has the knowledge, the interest in participating in a future European air-breathing aerospace vehicle development effort, and a good working relationship with the European Space Agency and other European companies likely to be involved in such an effort.

A Fiat Aviazione official described the 1988 feasibility study as an investigation and analysis of available design technologies for air-

breathing engines for both single- and two-stage-to-orbit systems. The study also included a performance simulation of turboramjets, turbo-soramjets, turborockets, and ram-rockets at various speeds and altitudes. Potential problems were identified in the areas of materials, temperature, air intake, and combustion. Finally, the study included an analysis of facilities and tools needed to test these engine concepts.

Fiat Aviazione officials concluded from the study that the most feasible concept is a two-stage-to-orbit space launch vehicle. On the basis of an analysis of engine performance and fuel consumption, among other variables, Fiat Aviazione officials also concluded that a turboramjet is the best propulsion alternative. They noted that no company or country in Europe has the capability to test all of the parameters of a turboramjet, but European facilities do exist to test various individual aspects of engine performance (such as combustion, temperature, and airflow).

After it completed the preliminary feasibility study for the Italian government, Fiat Aviazione continued its research efforts to obtain additional information on air-breathing engines. This information included available design technologies for various air-breathing engines, performance simulations, and facilities and tools needed to test these engines.

Fiat Aviazione plans to continue its research on air-breathing propulsion and submitted a proposal for the second phase of the feasibility study to the Italian Space Agency. According to a Fiat Aviazione official, the company also wants to combine its research with that of Messerschmitt-Boelkow-Blohm and Motoren- und Turbinen-Union's research on Saenger II. If this occurs, then Fiat Aviazione and the two German companies would conduct more detailed bilateral investigations, simulations, and tests on available design technologies until 1993; develop a technology flight demonstrator between 1993 and 1999; and flight test a full-scale engine beginning in the year 2004. This proposal parallels Germany's Hypersonic Technology Program.

Aeritalia is collaborating with Messerschmitt-Boelkow-Blohm in exploratory studies of a subscale hypersonic demonstrator aircraft that would be used to validate design and propulsion system concepts for Saenger II. Aeritalia has set up a joint working group with the German company to explore the technical feasibility of producing and flying the hypersonic demonstrator.

## Advanced Materials

The second most critical enabling technology is advanced materials. The weight of an aerospace vehicle must be reduced as much as possible to minimize the fuel and thrust required by the engine. Also, hypersonic flight causes extremely high temperatures due to air resistance on the vehicle's surfaces and within the engine. For example, the X-30's nose cone could reach more than 5,000 degrees Fahrenheit, and the leading edges of the wing and tail could reach almost 3,500 degrees Fahrenheit. Therefore, materials must be developed that are able to withstand extremely high temperatures and are high-strength, lightweight, and reusable. Advanced materials include carbon-carbon, titanium-based alloys, fiber composites, and titanium aluminum (ti-aluminide) produced by rapid solidification technology.

According to the Department of Defense, ongoing research and development in Europe indicate a potential capability of making major contributions to meeting U.S. challenges and goals in advanced materials. These include

- development of composite materials capable of retaining structural properties at high temperatures,
- application of structural composites to reduce observables,
- development of improved nondestructive evaluation techniques for advanced composites,
- improvements in characterization of composite material response to weapon effects, and
- improvements in modeling and prediction of life-cycle failure.

European countries have active advanced materials development programs and may lead the United States in selected aspects of advanced materials research. However, according to the Department of Defense, the United States has the overall lead in the design and effective use of advanced composite materials in specific military applications. Primary opportunities for U.S. cooperation with European countries will occur in the area of ceramic composites and in selected processing technologies.

In the past, Europe followed the U.S. lead in applying advanced materials to military systems, but the use of composites is already well established in Europe. The industrially advanced West European countries have also become important suppliers of advanced materials to the United States. For example, the French are among the world's leaders in production of ceramic composites and have initiated a joint venture with a U.S. company. The United Kingdom, Germany, and Switzerland have active programs in advanced materials research.

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According to the Department of Defense's Critical Technologies Plan,<sup>3</sup> the United States is judged to be the world's leader in composite materials. However, its lead is being rapidly eroded by a combination of industrial technology transfer and strong research and development efforts by foreign countries. The rate of technology flow among companies and between countries is likely to increase due to the increasingly multinational character of the materials industries.

European aerospace vehicle concepts do not plan to use rapid solidification technology powder metallurgy such as ti-aluminide. Although the National Office for Aerospace Studies and Research has limited rapid solidification technology production capability for ti-aluminide (about 200 pounds per year), we did not find any European propulsion or air-frame company conducting research or building rapid solidification technology facilities to manufacture production-level quantities of ti-aluminide.

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## France

Several French companies are involved in advanced materials research and development activities. For example, Aerospatiale is developing a thermal protection system for Hermes that will consist of a carbon-carbon nose cone and leading edges. Other suppliers will provide silica mattresses for Hermes' upper side as part of the thermal protection system. Another manufacturer is providing silicon carbide matrix shingles for Hermes' thermal protection system. Mica sheets are also being used in the shingles. Aerospatiale also manufactures ceramic nuts and bolts but has not decided on the need for ceramic-reinforced fasteners. Aerospatiale is working on nickel- and cobalt-based refractory metal structures and medium temperature-reinforced composites by comparing various fibers and matrices at 200 to 300 degrees Celsius. According to Aerospatiale officials, the company is not creating new materials but rather is developing manufacturing processes. Aerospatiale is working with thin sheet alloys to manufacture sandwich structures using three main processes: spot welding, brazing, and laser welding. Aerospatiale also has experience in three-dimensional weaving and producing quantities of carbon matrices for missiles. Avions Marcel Dassault-Breguet Aviation has been developing hot structures and materials, particularly ceramic tiles for Hermes.

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<sup>3</sup>The third Annual Defense Critical Technologies Plan is a plan for developing the 21 critical technologies considered by the Secretary of Defense and the Secretary of Energy to be the technologies most critical to ensuring the long-term qualitative superiority of U.S. weapon systems and to outline an investment strategy to manage and promote the development of these technologies. See Department of Defense. Critical Technologies Plan. Washington, D.C.: Department of Defense, 1991.

Work on composite materials is a major activity for the European Propulsion Company, which began carbon-carbon development in the 1960s. According to a company official, its facility in Bordeaux, France, is the largest in the world for composites and is primarily used to test composite materials for Hermes. The European Propulsion Company has new codes for manufacturing new material designs. In addition, the company has developed parts for air-breathing and combined engines using silicon carbide fiber and matrix materials. The company is also looking at active cooling for composite materials using hydrogen. Company officials concluded that composite ceramic-ceramic materials (a ceramic matrix reinforced by long fibers) are the key to efficient and lightweight engines needed for the next generation of space transportation systems. According to a company official, the company is not involved in work using metallic matrices, ti-aluminide, or rapid solidification technology.

The National Company for the Study and Construction of Aviation Engines is beginning research on titanium-dispersoide. The company is not involved in any other materials research, according to a company official.

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## Germany

Under the Hypersonic Technology Program, the Federal Ministry for Research and Technology is proposing the (1) development and testing of primary structure components made of titanium for use at temperatures up to 700 degrees Centigrade, (2) efficient production of components made of carbon fiber-reinforced carbon and oxidation-protection layers for use at temperatures up to 2,000 degrees Centigrade, (3) production of components made of fiber-reinforced ceramics, and (4) development and production of tank structures for liquid hydrogen. The German Aerospace Research Establishment is considering plans to develop new materials, and Motoren- und Turbinen-Union plans to try to improve titanium to withstand high temperatures.

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## United Kingdom

According British National Space Centre officials, different advanced materials are needed for different parts of HOTOL. For example, these officials said that nickel alloys, ceramics, and carbon-carbon can be used for the leading edges; cobalt alloys for the lower surfaces; and titanium for the upper surfaces. In addition, one British National Space Centre official said that some parts of HOTOL's body may not have to withstand high temperature because HOTOL is dense, resulting in lower temperatures. According to a British Aerospace official, some materials used for

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HOTOL include carbon-reinforced plastics for cryogenic tanks, intermetallics for intermediate temperatures, and ceramics.

Under the 2-year HOTOL proof-of-concept study, British Aerospace studied advanced materials including metal matrices and carbon-carbon for thermal protection panels. In addition, an official from British Aerospace told us that six British companies are involved in a materials qualification program for developing various types of materials including carbon-carbon and carbon-fiber. The company official also said that an extensive British university materials qualification program is underway.

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## Italy

In 1988 Aeritalia submitted a proposal to the Italian Space Agency to conduct research on advanced materials. Aeritalia officials stated that the company is specifically interested in ceramic composite matrices and plans to develop the capability to shape and test these materials. Under the Ferri Project, Aeritalia plans to concentrate its efforts on basic materials development to be used on thermal protection systems. Aeritalia expects to concentrate on load-carrying hot ceramic structures.

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## Computational Fluid Dynamics and Supercomputers

Computational fluid dynamics—the use of advanced computer programs to solve a set of mathematical equations with a high-speed digital computer—is extensively used in aerospace vehicle programs to simulate air flows, high temperatures, and pressure contours around various design configurations of an aerospace plane and within advanced propulsion systems at high Mach speeds. These calculations are used in the design of the vehicles' airframe and engine.

Computational fluid dynamics is also used to simulate aerospace vehicle performance between speeds of Mach 8 and 25, where ground test facilities or capabilities are not adequate in terms of velocity duplication and actual test data are limited. Computational fluid dynamics computer programs must also be validated by actual test data at lower speeds, which are then compared to the theoretical calculations. Modifications to the computer programs are then made where appropriate.

Advances in supercomputers over the past several years have allowed extensive use of computational fluid dynamics in European aerospace vehicle research and development programs. Use of supercomputers has resulted in more accurate and faster air flow calculations.

The United States currently has a commanding lead in computational fluid dynamics, according to the Department of Defense. However, Europe is developing a competitive capability, since computational fluid dynamics is recognized worldwide as a critical technology. Computational fluid dynamics is a powerful tool for modifying designs and solving problems, and its use by the U.S. aerospace industry for the design of the next-generation commercial aircraft is expected to help maintain the current U.S. dominance.

National Aeronautics and Space Administration officials cautioned that the United States does not have a commanding lead in all aspects of computational fluid dynamics. They suggested the U.S. lead is largely in hardware rather than in software, algorithms, and modeling. They noted that some leading edge work is going on in Europe. In fact, according to a National Aeronautics and Space Administration official, the last two major breakthroughs in computational fluid dynamics have come from the United Kingdom.

According to the Department of Defense's Critical Technologies Plan, ongoing research and development in the following areas of this technology indicate a potential capability by European countries to make some contributions in meeting U.S. computational fluid dynamics challenges and goals:

- improvement in the abilities to apply computational fluid dynamics to complex three-dimensional aerothermodynamic analyses (including characterization of chemical reactions),
- empirically validated codes for three-dimensional analysis of material response to high-strain/high-deformation rates, and
- development of algorithms and programming tools to exploit massively parallel computing architectures.

According to the Department of Defense, cooperative opportunities will exist with European countries, especially in the area of specific algorithm developments. Moreover, if European countries proceed with development of several different aerospace plane concepts, then further opportunities for cooperation will become available. Secondary opportunities for cooperation in computational fluid dynamics technologies may also be available in other countries, including Italy and Sweden.

European countries have had considerable success in the practical use of computational fluid dynamics to develop better designs for gas turbine engines, new transport and business jets, and jet trainers. According to

the Department of Defense, this capability for exploiting computational fluid dynamics is comparable with methods in the United States. European countries have both the expertise in numerical methods as well as the most powerful U.S. supercomputers.

Much of the basic scientific knowledge about computational fluid dynamics is well known in Europe. The United Kingdom is considered by the Department of Defense to have the greatest experience among European countries in applying computational fluid dynamics to weapon systems. Germany, Italy, and France also have strong computational fluid dynamics capabilities. As the number of supercomputers and European research and development of aerospace vehicles increase in the 1990s, the European's ability to advance the field of computational fluid dynamics is expected to dramatically improve.

Knowledge of sophisticated algorithms, as well as the methods for practical exploitation of computational fluid dynamics, is widespread within Europe. For example, France is the pioneer in Europe in finite element methods for complex aircraft configurations and is a leader in computational fluid dynamics development for turbulent simulations and modeling. The United Kingdom has efficient methods for transonic flow. Germany is pioneering computations with the full Navier-Stokes codes and is applying them to analysis of hypersonic flight. The Netherlands has an extensive effort in developing algorithms for parallel processing. Italy is also contributing to the state of the art in computational fluid dynamics by conducting numerical research activities and developing software for use in the aerospace research fields of fluid dynamics, structures, propulsion, and flight mechanics. Italian universities were involved in Phase II of the Ferri Project's 1989 feasibility study as well by conducting computational fluid dynamics research. The Italian Aerospace Research Center also planned to install the Italian Aerospace Supercomputer facility complex by 1990.

Formal exchange of information about computational fluid dynamics between the United States and Europe is limited; however, much of the computational fluid dynamics research into numerical techniques and algorithms is conducted in the academic environment. Many of the empirically validated computational fluid dynamics codes that can be used for practical applications are proprietary. Among the U.S. military services, the U.S. Air Force is the primary proponent for computational fluid dynamics exchanges. It already has agreements with several European countries in key areas. Computational fluid dynamics is also

expected to benefit at least indirectly from many of the exchange programs in propulsion and materials.

## Technological Challenges

European industry and government officials identified several areas in which more research or technology maturation is required to develop an air-breathing aerospace vehicle. For example, National Company for the Study and Construction of Aviation Engines and European Propulsion Company officials consider temperature control of hydrogen for the engine, engine/airframe integration, computational fluid dynamics, and the technology for hydrogen tanks as critical. Avions Marcel Dassault-Breguet Aviation officials mentioned thermal protection, engine/airframe integration, and telepiloting as technological challenges, whereas Aerospatiale officials cited active cooling of hot structures.

National Company for the Study and Construction of Aviation Engines and European Propulsion Company officials described several critical technologies for advanced propulsion that are common problems for a variety of engine types. These include high performance of air inlet and nozzles, mechanical/functional integration of engine modes/cycles, mixing of supersonic/subsonic reactive gases, cooling systems and heat exchanger technology, composite materials, and turbine efficiency for supersonic turbine design. In addition, a National Office for Aerospace Studies and Research official identified engine test facilities for all speeds, including those of scramjet engines, as another challenge concerning propulsion.

Several officials identified advanced materials as a technological challenge. For example, National Center for Space Studies officials said the need to build a light, but strong, vehicle is a major challenge. An Aerospatiale official said more work is needed on metallic structures and refractory metals. European Space Agency officials said technology maturation is needed in structures because no advanced work in this field is associated with the Hermes program.

National Center for Space Studies officials also described the economics of air-breathing aerospace vehicle development as a challenge. They said the investment costs will be enormous, the operational costs high, and the payloads small. Because the maximum payloads would be between 6 and 7 tons, conventional launchers would still be needed.

According to German government and industry officials, several areas require more research or technology maturation to develop an air-

breathing aerospace vehicle. According to the Federal Ministry for Research and Technology and industry officials, technological challenges include aerothermodynamics, systems engineering, and airframe capacity. Technological challenges related to propulsion include problems with the nozzle, air intake, and combustion. The Federal Ministry for Research and Technology also identified the development of advanced materials as a technological challenge. Such materials include high temperature-resistant carbon-carbon composites, composites with a metallic matrix, and fiber-reinforced ceramics.

British National Space Centre officials said that the 2-year study showed that HOTOL could be developed but that, as expected, additional research was needed on those technologies critical to developing an air-breathing aerospace vehicle: propulsion, materials, and structures. In propulsion, more research is needed in engine development and integration, according to a Centre official. In materials, new cost-effective advanced materials must be developed to withstand high temperatures, according to a British Aerospace official. Additionally, a Centre official said more work must be done in avionics, and British Aerospace officials consider command and control and aerodynamics to be technological challenges.

# U.S. and European Investment in Aerospace Vehicle Research and Technological Development Efforts

Although directly comparable data for U.S. and European investment in aerospace vehicle research and technological development efforts are not available, funding levels and the number of people involved indicate that U.S. investment in the NASP Program in these areas far exceeds that of any European country or the European Space Agency in their aerospace vehicle programs. Moreover, planned funding and personnel levels indicate that U.S. investment in the NASP Program will continue to exceed that of any European country or the European Space Agency in their programs.

## U.S. Investment in the NASP Program

The NASP Program is expected to cost more than \$5 billion between fiscal years 1986 and 1997, according to the NASP Joint Program Office. The United States has spent about \$1.8 billion on the NASP Program between fiscal years 1986 and 1990. Of this amount, the U.S. government has invested almost \$1.1 billion and U.S. industry about \$736 million. According to the NASP Joint Program Office, more than 5,500 people in government, industry, and academia are working on the NASP Program.

The U.S. government also plans to spend about \$2.7 billion on the NASP Program from fiscal years 1991 to 1997. Future U.S. industry contributions, however, are expected to be marginal, according to a NASP Inter-agency Office official, since a national contractor team<sup>1</sup> has been established and companies are no longer in competition. The NASP Inter-agency Office expects another \$457 million to be contributed by the National Aeronautics and Space Administration between fiscal years 1994 and 1997 and U.S. industry between fiscal years 1991 and 1997.

<sup>1</sup>In May 1990 the Department of Defense and National Aeronautics and Space Administration approved a proposal by the five NASP prime contractors to form a single NASP team. The national contractor team consists of General Dynamics Corporation (airframe development), McDonnell Douglas Corporation (airframe development), Rockwell International Corporation's North American Aviation Division (airframe development), Rockwell International Corporation's Rocketdyne Division (engine development), and United Technology Corporations' Pratt & Whitney (engine development). The National Program Office was also established to integrate the contractor team's work and serve as a single point-of-contact for the government with the contractor team on contractual and technical matters.

## European Space Agency and European Countries' Investment in Aerospace Vehicle Programs

European Space Agency members' contributions to Hermes and its Ariane 5 launch booster are more of an investment in shuttle-like and conventional rocket technologies than a direct investment in air-breathing aerospace plane technologies. As discussed in chapters 1 and 3, Hermes would serve as a technology demonstrator, have an operational capability, and be an intermediate step in developing a future European air-breathing aerospace plane.

European Space Agency members' contributions to the Preparatory Program of Ariane 5 totaled about \$775 million between 1986 and 1988. European Space Agency members' contributions to the Hermes program are expected to total about \$748 million between 1986 and 1991 (about \$116 million for the Preparatory Program between 1986 and 1988 and about \$632 million for Phase 1 of the Development Program between 1988 and 1991).

The French government has spent between about \$13.4 million and about \$16.4 million and French industry reportedly has invested about \$2.3 million on air-breathing aerospace vehicle concept studies between 1986 and 1990. The German government has spent about \$85.5 million between 1982 and 1990 (\$8.5 million on hypersonics between 1982 and 1987 and about \$77 million on Phase 1 of the Hypersonic Technology Program between 1988 and 1990). German industry has spent an additional \$3.2 million. The British government has spent about \$3 million and British industry has provided an additional \$15 million on a proof-of-concept study for an air-breathing aerospace vehicle between 1986 and 1990. The Italian government has spent between about \$1 million and about \$1.4 million and Italian industry has contributed about \$292,000 for air-breathing propulsion research between 1988 and 1989. The Dutch government has spent about \$4 million on its technology program during 1988. The Belgian government and industry have not invested any funds in aerospace vehicle research and development efforts. Belgium's von Karman Institute for Fluid Dynamics spends about \$5 million annually on its testing activities.

The European Space Agency plans to spend about \$4.2 billion on the Ariane 5 Development Program between 1988 and 1995 and about \$4.8 billion on Phase 2 of the Hermes Development Program between 1991 and 1997, if approved by its member states in 1991. Again, these planned levels of investment for Ariane 5 and Hermes are not for air-breathing aerospace plane programs or technologies.

If a decision is made to continue air-breathing aerospace vehicle concept studies and technology development, the French government plans to spend from \$20 million to \$30 million between 1990 and 1992 and industry an estimated \$5 million from 1988 to 1992 on hypersonics. The German government plans to spend about \$131 million on the Hypersonic Technology Program between 1991 and 1992. During that same period, an additional \$23 million is expected to be provided by the German Research Association and state ministries and about \$25 million by German industry. No new funding is planned by the British government for HOTOL. British industry investment is uncertain, but British Aerospace provided about \$700,000 in 1989 to keep the HOTOL program going while international partners were sought. British Aerospace expects to spend between \$1 million and \$3 million in 1990 and 1991 for the Interim HOTOL project. According to Italian Aerospace Research Center officials, the Italian government plans to invest about \$575 million in facilities in 1990 and between \$36 million and \$48 million in Germany's Saenger II program between 1991 and 1992 once a government-to-government agreement is signed. Dutch government investment in its technology program was expected to increase to about \$6 million by 1990. The Belgian government and industry do not plan to make any direct investments in aerospace vehicle research and development efforts in the future.

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### **Funding of European Space Agency Aerospace Vehicle Programs**

A European Space Agency official stated that about \$456,000 was available during 1988 for the European Space Agency's study of space transportation systems. The official said that industry participants contributed an additional \$342,000 during 1988.

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### **European Space Agency Member States' Investment in Hermes**

Funding for Ariane 5 and Hermes through Phase 1 of the Development Program was approved at the European Space Agency Ministerial Council meeting at The Hague, The Netherlands, in November 1987. Table 5.1 shows the percent and amount European Space Agency member states have agreed to contribute to the Hermes Preparatory Program (1986 to 1988) and Phase 1 of the Development Program (1988 to 1991).

**Table 5.1: European Space Agency Member States' Contributions to the Development of Hermes**

Dollars in millions

Member state	Preparatory Program <sup>a</sup>		Development Program <sup>b</sup>		Total
	Percent	Amount	Percent	Amount	
France	37.29	\$43.6	43.50	\$275.2	\$318.8
Germany	26.63	31.2	27.00	170.8	202.0
Italy	13.32	15.6	12.10	76.5	92.1
Belgium	5.68	6.6	5.80	36.7	43.3
Spain	4.97	5.8	4.50	28.5	34.3
The Netherlands	3.55	4.2	2.20	13.9	18.1
Switzerland	1.78	2.1	2.00	12.7	14.8
Sweden	2.22	2.6	1.30	8.2	10.8
Canada	0.98	1.1	0.45	2.8	3.9
United Kingdom	2.99	3.5	0.00	0.0	3.5
Austria	0.06	0.1	0.50	3.2	3.3
Denmark	0.35	0.4	0.45	2.8	3.2
Norway	0.00	0.0	0.20	1.3	1.3
Ireland	0.18	0.2	0.00	0.0	0.2
Finland	0.00	0.0	0.00	0.0	0.0
<b>Total</b>	<b>100.00</b>	<b>\$117.0</b>	<b>100.00</b>	<b>\$632.6</b>	<b>\$749.6</b>

<sup>a</sup>The Preparatory Program was from 1986 to 1988.

<sup>b</sup>The Development Program (Phase 1) is from 1988 to 1991.

As of September 1990, Phase 2 of the Hermes Development Program was expected to cost about \$4.8 billion between 1991 and 1997.

## European Space Agency Facilities and Number of Employees

The European Space Agency, as of December 1990, had 1,978 employees, including 392 who worked at its headquarters in Paris. It has three major facilities: the European Space Research and Technology Center in Noordwijk, The Netherlands; the European Space Operations Center in Darmstadt, Germany; and the European Space Research Institute in Frascati, Italy. The European Space Agency also has personnel at each member state's national space organizations. Additional European Space Agency staff members (included in the headquarters total above) are also located at the Earth Observation Program Department in Toulouse, France; the European Astronauts Centre in Koln-Porz, Germany; the launch site in Kourou, French Guiana; and the Washington Office in Washington, D.C. France's National Center for Space Studies, which owns the Kourou launch site, leases the launch site to Arianespace, which operates it for the European Space Agency.

The European Space Research and Technology Center has a staff of 1,159 and is responsible for spacecraft environmental testing, managing various spacecraft projects, and performing applied science research. The Center has an additional 300 contract personnel also located in Noordwijk, The Netherlands.

The European Space Operations Center has a staff of 319 (including its ground stations) and is responsible for all European Space Agency satellite operations as well as all European Space Agency ground sites and communications networks. European Space Agency ground sites are located at Michelstadt, Germany; Redu, Belgium; Villafranca, Spain; Kourou, French Guiana; Carnarvon, Australia; Ibaraki, Japan; Malindi, Kenya; Fucino, Italy; and Kiruna, Sweden.

The European Space Research Institute has 108 staff members that operate the Information Retrieval Service. The European Space Information Service was established at the Institute as a central archival and cataloging site for European Space Agency scientific data.

## French Government, Industry, and University Investment

The National Center for Space Studies did not invest in air-breathing research and development before 1986, according to French space agency officials. The Center spent an estimated \$10 million between 1986 and 1988 for the systems study and planned to provide an additional \$3 million to \$4 million in 1989. Center officials said investment could double or triple between 1990 and 1992 to begin limited technology development of an air-breathing aerospace plane. A French space agency official told us that the French government could possibly invest in an air-breathing aerospace plane program, if it is a basic research and technology program. However, the official said that it is doubtful that the French government will invest in an air-breathing aerospace vehicle program, since the government is too committed to Hermes.

The National Center for Space Studies is headquartered in Paris and has a total work force of about 2,200 to 2,500. The Center's Launch Vehicle Directorate is located in Evry, France, and is responsible for development of the Ariane launch vehicle. The Toulouse Space Center in Toulouse is the Center's main engineering and technology facility and has about 1,500 employees. This facility operates the balloon launch centers at Aire-sur-l'Adour and Gap Tallard, France. The Guiana Space Center in Kourou, French Guiana, is the European Space Agency's South American launch site for the Ariane launch vehicle. Also, space science research and development are conducted under contract to the Center

by 11 principal space laboratories with some 1,500 to 2,000 personnel. In addition, the Center has formed 14 wholly or partially owned subsidiaries for commercial and marketing activities, the most prominent of which is Arianespace.

In November 1989 the French Ministry of Research and Technology announced that it was investing about \$2.4 million to coordinate diverse research efforts undertaken by Aerospatiale, Avions Marcel Dassault-Breguet Aviation, National Company for the Study and Construction of Aviation Engines, European Propulsion Company, and National Office for Aerospace Studies and Research.

In 1990 the National Office for Aerospace Studies and Research had planned to invest about \$10 million per year in hypersonic research. This figure includes about \$1 million that is directly related to funding for a future spaceplane beyond Hermes. The National Office for Aerospace Studies and Research's total budget for 1990 was about \$235 million in operating funds and about \$50 million in investment funds for refurbishing and upgrading existing facilities and for building new ones. Of the \$235 million, about 40 percent, or about \$94 million, is allocated for aircraft and about 14 percent, or about \$32.9 million, is allocated for space. The amount allocated for space has been increasing since 1986.

In 1990 the National Office for Aerospace Studies and Research had 2,275 employees (2,170 were full-time), about two-thirds of which were scientists or high-level engineers and technicians. Office facilities are located near Paris at Chatillon-sous-Bagneux (headquarters and main laboratories with 1,060 employees), Chalais-Meudon (research wind tunnels with 250 employees), and Palaiseau (research facilities for propulsion and system studies with 260 employees). The Office's Modane-Avrieux Centre near Modane contains the large wind tunnels and employs 235 persons. The Centre d'Etudes et de Recherches de Toulouse, or Toulouse Research and Study Center, has 275 employees. The Office's Le Fauga-Mauzac Centre, located near Noe (south of Toulouse), has 75 personnel and contains new large testing facilities. It will play an increasing role in research in the fields of aerodynamics and propulsion. Finally, the Institut de Mecanique des Fluides de Lille, or Lille Institute of Fluid Mechanics, houses the Office's flight mechanics facilities, research wind tunnels, and structures laboratories and has a staff of about 120.

Aerospatiale officials said their company invested about \$1.5 million in future aerospace vehicle research from 1982 to 1987 and contributed

about \$500,000 to the study conducted by the National Center for Space Studies in 1988. Additionally, Aerospatiale spends about \$2 million annually on computational fluid dynamics and materials research. Aerospatiale officials said the company may invest about \$5 million between 1988 and 1992 on future aerospace vehicle research. The officials said they cannot predict expenditures beyond that, but Aerospatiale will not increase expenditures above the present level.

According to Avions Marcel Dassault-Breguet Aviation officials, the company did not fund hypersonic research before its involvement in Hermes. In 1988 the company contributed about \$336,000 to the National Center for Space Study's systems study. Less than 10 company employees are involved in the study. Future investment depends on the availability of funding from the French government and opportunities for participation in the NASP Program, the officials stated.

Investment information from the National Company for the Study and Construction of Aviation Engines and the European Propulsion Company was not available. Hyperspace, the new consortium created by these companies to coordinate their propulsion system studies for hypersonic aircraft, expects to begin work in 1992 with annual funding totaling about \$26 million.

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## German Government, Industry, and University Investment

The German Space Agency was established in April 1989 with a staff of about 15 and a budget of \$12.5 million. As of October 1990, the Agency had a staff of about 60. Once the Agency has reached its final size, it will have between 300 and 370 employees. By 1992 the Agency's budget for all space programs is expected to approach about \$1.3 billion annually. The Federal Ministry for Research and Technology, which has managed Germany's space program in the past, provides about 90 percent of the Agency's budget. Funding for Germany's domestic space programs as well as its contributions to the European Space Agency will come out of the Agency's budget.

Between 1982 and 1987, the Federal Ministry for Research and Technology spent about \$8.5 million on technical concept studies for the three-phased Hypersonic Technology Program. The estimated cost of Phase I of the program (from 1988 to about 1992) is about \$233 million: \$102 million for propulsion systems, \$45 million for aerothermodynamics, \$40 million for concept studies, \$33 million for materials/construction methods, and \$13 million for flight management and systems.

According to a Federal Ministry for Research and Technology official, the Ministry cannot afford to fund the entire program but can probably provide about \$125 million. The Ministry is funding 100 percent of the system concept studies and development of propulsion technologies. However, the Ministry is funding only 80 percent of the individual technology projects. German industry is funding the remaining 20 percent (about \$25 million) for such projects until 1993. According to the Ministry, the requirement for 20-percent direct participation by industry in technology projects is justified by the substantial increase in technology potential for aviation products and other spaceflight applications.

According to the Ministry's Director of Aeronautical and Spaceflight Technologies, 45 percent of the Ministry's \$125 million contribution, or about \$56.3 million, is used for studying general hypersonic design concepts, whereas 43 percent, or about \$53.8 million, is spent on technology studies by German industry. The remaining 12 percent, or about \$15 million, is being spent to develop test facilities. The Ministry also plans to contribute about \$34 million for work on the HYTEX technology demonstrator vehicle.

The German Aerospace Research Establishment plans to contribute about \$49 million in direct allocations to the Hypersonic Technology Program and make personnel available for work on this program. With a staff of about 4,400, the Establishment is the largest engineering science research organization in Germany. The Establishment has research programs in three key areas: aeronautics, space technology, and aerospace-related technologies. Its facilities and installations are located at five centers (Oberpfaffenhofen, Koln-Porz, Braunschweig, Goettingen, and Stuttgart) and six local branches (Hamburg, West Berlin, Trauen, Bonn, Lampoldshausen/Hardthausen, and Weilheim).

About \$23 million is expected to be provided by the German Research Association and state ministries for the Special Research Field Project between 1990 and 1992. These funds are divided between the four "centers of excellence" (the Rheinland-Westfalia Technical University of Aachen, the University of Stuttgart, the Technical University of Braunschweig, and the Technical University of Munich), as well as the University of the Armed Forces in Munich, to study technologies critical to the development of an aerospace vehicle. A University of Stuttgart official told us that research at that university is estimated to cost about \$3 million per year.

Messerschmitt-Boelkow-Blohm officials said the company invested about \$6 million between 1982 and 1987 for all work (military and civil) on ram-rockets and ramjets. In addition, the company has invested about \$34 million on test facilities over the last 20 years. Messerschmitt-Boelkow-Blohm also spent about \$1 million on a propulsion study in 1988, according to a company official. Motoren- und Turbinen-Union officials said their company did not invest in hypersonics in the past. Investment information for Dornier was not available.

As a result of the potentially high costs associated with German reunification on October 3, 1990, all sectors of German government spending are being reevaluated, including the space budget, which is receiving intense scrutiny. According to a Federal Ministry for Research and Technology official, the German space budget is not likely to increase substantially in the next 2 to 3 years because of the costs of rebuilding the former German Democratic Republic. Scientists, engineers, technicians, and companies from the former East Germany are being integrated into former West German space programs, which became Germany's current programs.

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## **British Government, Industry, and University Investment**

According to a British National Space Centre official, the Centre provided \$3 million to evaluate HOTOL in 1986 and 1987. British Aerospace contributed about \$5 million and Rolls-Royce about \$2 million to the study during that period. In addition, British Aerospace had between 70 and 100 people working on HOTOL, and Rolls-Royce had about 15 people working on the HOTOL propulsion system.

A British National Space Centre official told us that the British government had not provided funds for HOTOL research since 1988. The official said the British government withdrew funding for HOTOL research in July 1988 because government officials believed that HOTOL development was too expensive. The Counselor for Scientific and Technological Affairs at the U.S. Embassy in London told us that the British government is likely to fund short-term efforts with immediate payoffs and not long-term projects, such as HOTOL.

The British National Space Centre encouraged industry to fund HOTOL research from 1988 to 1990 and seek international partnerships. According to Centre officials, the British government will help industry find international partners and may review its position on providing funding if the possibility of an international partnership emerges. A

British Aerospace official said the government promised to consider participating in a properly organized international venture, but Centre officials said the government has not promised to fund such a venture.

Despite the lack of government funding, British Aerospace plans to continue its HOTOL research efforts. In 1988 a British Aerospace official told us that the company allocated about \$4 million and between 70 to 100 people to work on the HOTOL project. For 1989 the company planned to make the same investment it did in 1988. However, after failing to find commercial backers 1 year after the British government decided not to provide further funds, British Aerospace is reducing its support for HOTOL. According to British Aerospace's Director of Business Development, the company has reduced the number of people on its HOTOL scientific and engineering team from more than 100 in 1988 to about 15 in 1990.

With HOTOL facing termination, British Aerospace and the Soviet Ministry of Aviation Industry's new initiative begun in September 1990 to conduct a 6-month joint study of the feasibility of air-launching an interim version of HOTOL from the back of the Soviet Union's Antonov An-225 heavy-lift transport aircraft will require additional British Aerospace investment in HOTOL until 1991. According to a British Aerospace official, the company plans to invest between \$1 million and \$3 million for the study. The official indicated that the Soviet Ministry of Aviation Industry plans to invest a similar amount. As of November 1990, British Aerospace had 20 to 25 people working on the Interim HOTOL project and expected to have about 100 people working on this project during wind tunnel testing.

In 1988 Rolls-Royce had about 10 people working on the HOTOL propulsion system to support British Aerospace's continuing efforts, according to a Rolls-Royce official. In 1989 Rolls-Royce did not plan to provide funds or resources for HOTOL. However, according to the company official, Rolls-Royce will continue to invest in technological research that could indirectly benefit HOTOL research. Between 1985 and 1988, Rolls-Royce invested about \$27 million in materials research. However, according to Rolls-Royce's Chief Engineer for High-Speed Propulsion Projects, Rolls-Royce has not directly invested in HOTOL since 1989. The Chief Engineer also said that no other organization had been found to sponsor such work.

## Italian Government, Industry, and University Investment

The Italian Space Agency did not make any investments before 1988 in research and development of air-breathing aerospace vehicles. In 1988 the Agency provided about \$292,000 for Phase I of the feasibility study on air-breathing propulsion conducted by Fiat Aviazione. The company also contributed about \$292,000 to the study that year. According to an Agency official, in 1989 the Agency planned to fund between \$767,000 and \$1.15 million for Phase II of the feasibility study. However, the amount depended on submission and approval of proposals by Fiat Aviazione and Aeritalia. Agency officials said in November 1988 that it is too early to determine how much it will invest in such research beyond 1989, since the agency is still in a transition stage. Nonetheless, Agency officials stated that resources for hypersonics would be increased in anticipation of a sizeable effort over the next few years. Fiat Aviazione and Aeritalia officials said that neither company planned to use its own funds in 1989 for the feasibility study.

The Italian government approved special legislation for financing Italian Aerospace Research Center facilities and planned to invest about \$575 million in 1990 for the facilities necessary to give the Center an operational capability. This amount includes about \$45 million for construction of the Center's Low-Speed Wind Tunnel, about \$120 million for the its High Reynolds Transonic Wind Tunnel, and about \$23 million out of the approximately \$50 million total cost for its Plasma Wind Tunnel. The European Space Agency plans to contribute the balance of about \$30 million. In addition, the transonic extension to the Center's Low-Speed Wind Tunnel will cost about \$23 million, but this amount is not included in the current funding plan. The \$575 million total also includes funds for a multiprocessor Cray YMP supercomputer facility at the Center's Headquarters in Capua (the Center already owns an ETA 10 supercomputer), technical laboratories, administration bays, and an electrical plant. The Center has already received about \$26.8 million from the Naples Regional Government to train its scientists.

The Italian Space Agency employs 150 to 200 people. The Italian Aerospace Research Center had 46 employees at the end of 1987 and as of November 1990 had 105 people. That figure is expected to grow to 230 by the end of 1991 and to 500 by the end of 1993. The Center also has about 60 people working in the computational field at its facility in Capua, Italy.

Aeritalia's proposals to the Italian Space Agency for funding of advanced research on computational fluid dynamics codes for the

Italian Aerospace Research Center's Plasma Wind Tunnel and for developing the capability to shape and test ceramic composite matrices total about \$15.3 million to \$30.7 million over a 5-year period between 1988 and 1993. About five Aeritalia employees have been working on this effort. If the Agency is not interested in this proposal, Aeritalia officials told us that they would seek funding from the European Space Agency or other European companies.

Fiat Aviazione's proposal for the second phase of the air-breathing propulsion feasibility study between 1988 and 1993 could cost between \$30.7 million and \$38.3 million. This phase would be jointly funded by Italy and Germany. Fiat Aviazione officials hope the Italian Space Agency will provide enough money for Fiat Aviazione to conduct its share of the research so that Fiat Aviazione does not have to invest any of its own funds. Currently, Fiat Aviazione has about 100 people working in space activities, including 90 in design engineering and 10 in production activities. Ninety percent of these employees are engineers, technicians, and instrumentation specialists. Fiat Aviazione would like to double the number of employees working in space activities to 200 by 1990 to 1992.

Bomprini Parodi Delfino-National Industrial Applications Corporation has not invested any of its own funds for air-breathing aerospace vehicle research, development, or testing. The company's participation in the 1987 European Space Agency-funded study to evaluate Europe's testing capabilities and problems to conduct air-breathing propulsion research totaled about \$23,000 out of the \$153,000 project cost.

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## **Dutch Government, Industry, and University Investment**

According to the Director of the Netherlands Institute for Aerospace Programs, the Dutch government does not conduct a specific technology development program aimed at aerospace vehicle enabling technologies. However, the Dutch government has conducted limited research in such technologies as advanced propulsion, advanced materials, structures, and hypersonic aerodynamics so that The Netherlands could participate in future European aerospace vehicle research and development efforts. The Institute's technology program totaled about \$4 million in 1988 and was expected to increase to about \$6 million by 1990.

The National Aerospace Laboratory has a work force totaling 784 people, 445 of which are located at the Laboratory's Headquarters in Amsterdam and 339 at the Laboratory's Nordoostpolder site near Markness.

Dutch universities are not conducting any research on air-breathing propulsion. However, the Delft University of Technology is conducting limited research on materials.

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## **Belgian Government, Industry, and University Investment**

According to U.S. Embassy officials in Brussels, the Belgian government has not invested any funds in air-breathing aerospace vehicle research and development efforts. According to Belgian industry representatives, Belgian companies have not made any direct investments in aerospace activities and do not plan to make such investments in the future. Belgian companies and universities, however, receive European Space Agency contracts for work on its programs.

The von Karman Institute for Fluid Dynamics's annual budget of about \$5 million (as of October 1990) is funded equally by the Belgian Ministry of Communications and Transport, 13 of the 16 North Atlantic Treaty Organization member countries, and independent research contracts. The Institute is currently staffed by 80 people including 13 faculty members and 21 technical personnel. In addition, the Institute now has about 60 postgraduate researchers.

# European Aerospace Test Facilities and Their Capabilities

Plans for the development of European aerospace vehicles such as the European Space Agency's Hermes spaceplane, Germany's Saenger II, the United Kingdom's HOTOL, and future air-breathing aerospace vehicle system and concept studies have renewed European interest in hypersonics. Also, the NASP Program is substantially responsible for the resurgence of interest in a field that had been relatively dormant in Europe for about 20 years. However, research and development of European aerospace vehicles and concepts require not only adequate test facilities and a comprehensive understanding of hypersonics but experienced and trained personnel as well.

This assessment of European aerospace test facilities and their capabilities includes wind tunnels and air-breathing propulsion test cells; advanced materials research, development, production, and fabrication laboratories; supercomputer facilities; and European facilities needed to test future aerospace vehicles.

## Wind Tunnels and Air-Breathing Propulsion Test Cells

To assess European hypersonic wind tunnel test facilities and their capabilities, a determination must be made whether the Europeans have the hypersonic wind tunnel facilities required to develop expertise in hypersonics and to develop and build future aerospace vehicles. Another determination that must be made is whether the Europeans have the experienced personnel to operate hypersonic wind tunnels.

According to a U.S. expert in hypersonics, the vigorous and enthusiastic development of hypersonic facilities and instrumentation in Europe in the 1950s and early 1960s abruptly ceased with the loss of interest in hypersonic aerodynamics in the late 1960s. Even though many of the facilities constructed in the 1950s still exist, many of the individuals involved in development of the facilities have retired or no longer work in this field. However, of those who remain, most have concentrated their research in the low-density regime in support of satellite and space station technology, whereas others used their hypersonic expertise in areas such as ballistics and missiles. In fact, according to one U.S. expert, European capabilities to perform experimental research in the low-temperature, rarefied flow regime may exceed those of the United States. The expert reported that, in this area, the European experimental facilities, instrumentation and recording equipment, and personnel are first-rate. However, no facilities are capable of exploring the hypervelocity low-density regime where there are critical design problems associated with real gas effects (changes in gas structure), viscous interaction (flow resistance), and catalytic wall effects (changes

that occur when the flow comes in contact with the wall of the body), which can significantly increase wall heating.

In contrast to its capabilities in low-density flows, European capabilities are very weak in addressing experimental problems for high-speed flows (high Mach numbers) and for high density and viscous flows (high Reynolds Numbers). European hypersonic facilities that could be used to address these problems are generally small and poorly supported. Many hypersonic facilities had not been used between 1975 and 1985, and, as a consequence, the instrumentation and technical support had diminished. According to a U.S. expert in hypersonics, a number of outstanding individual efforts can be found in Europe, but a rapid increase in funding and interest is needed for European hypersonic facilities to adequately support the European Space Agency's Hermes spaceplane and future air-breathing aerospace vehicle programs.

According to a U.S. expert in hypersonics who conducted an assessment of current European capabilities in hypersonics in 1986 for the U.S. Air Force European Office of Aerospace Research and Development in London, a significant capability exists in Europe to perform experimental research in low-density regimes associated with blunt body flows in hypersonic flight. However, there is little capability to investigate problems associated with hypervelocity flight at high altitudes. The expert concluded that at lower altitudes where there are critical aerothermal (flow and heat) design problems associated with transitional and turbulent boundary layers (the change in flow near the body from smooth to rough), European capabilities in facilities, instrumentation, and personnel are weak. The expert also concluded that only with the extremely rapid development of instrumentation and training of personnel, coupled with the renovation of some older facilities, will adequate support be available within Europe for the development of the European Space Agency's Hermes spaceplane or other air-breathing aerospace vehicles.

According to the Director of the von Karman Institute for Fluid Dynamics, Europe possesses a large range of hypersonic facilities, which, when renovation and modifications currently underway are completed, will constitute a sound basis for Mach number/Reynolds Number simulation. However, the Director believes that new facilities are needed in the long term to provide the capability to conduct refined design studies and to simulate at least some aspects of real gas effects. Non-intrusive instrumentation (which can make external measurements while not disturbing the flow) to aid in computational fluid dynamics

code validation and improved training programs are equally essential elements in a balanced program of hypersonic research and development in Europe.

All of the facilities capable of testing at speeds greater than Mach 12 have running times measured in milliseconds, which results in much poorer measurement accuracies than in low Mach number tunnels. Correspondingly, according to the Director of the von Karman Institute for Fluid Dynamics, productivity is generally low and the cost per data point is relatively high. According to the Director, all intermittent tunnels are, to some degree, dirty (contaminants in the test gas air leave a carbon build-up), and the erosive effects on test instrumentation may be severe.

According to the Director of the von Karman Institute for Fluid Dynamics, a major deficiency in European hypersonic facilities is apparent in velocity duplication, which is essential for accurate simulation of chemical effects. The Rheinland-Westfalia Technical University of Aachen Shock Tunnel comes closest to meeting the present needs to duplicate velocity. The National Office for Aerospace Studies and Research R6Ch Hypersonic Wind Tunnel project at Chalais-Meudon, which was planned in 1986, has been dropped and replaced by the F4 Hotshot Wind Tunnel, now under the final stages of construction at the Office's Le Fauga-Mauzac Centre near Toulouse. The F4 Hotshot will be a larger facility than the planned R6Ch. The F4 Hotshot will be a high-enthalpy, electric arc, hotshot-type facility. Nozzle exit diameter will range from 0.4 to 1 meter. High values of the kinetic parameter and of the viscous interaction parameter will be obtained with a run time duration of up to 50 milliseconds. The F4 Hotshot will be able to duplicate reentry velocities up to 4 to 5 kilometers per second. Its predicted performance in the Mach 7 to 18 range will provide the capability to simulate Reynolds Numbers equivalent to those of the Hermes flight envelope.

The F4 Hotshot will complement the S4MA Wind Tunnel, an intermittent, blowdown hypersonic wind tunnel at the Office's Modane-Avrieux Centre in Modane. The S4MA has recently been upgraded with a Mach 10 nozzle that has a 1-meter exit diameter. A Mach 12 nozzle is also expected to be operational in a short time. The S4MA is currently used to test Hermes and is considered by Avions Marcel Dassault-Breguet Aviation as the reference "cold" hypersonic wind tunnel in Europe.

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The German Aerospace Research Establishment's Hoch-Enthalpie-Kanals Goettingen, or Goettingen High-Enthalpy Tunnel, is scheduled to become operational in 1991. The facility is a Mach 7 free-piston shock tunnel that will produce flow velocities even greater than the F4 Hot-shot (up to 7 kilometers per second) but with testing times of 1 milli-second. The facility is similar in concept to the Rocketdyne Hypersonic Flow Laboratory shock tunnel at Rocketdyne's Santa Susana Field Laboratory near Los Angeles, California.<sup>1</sup>

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### Limitations in Ground Test Capabilities

Adequate ground test capabilities and facilities to test future air-breathing aerospace vehicles above speeds of Mach 8 for sustained periods do not exist anywhere. In fact, no single facility or group of facilities is capable of creating the combination of velocities, temperatures, and pressures necessary to simulate these aerospace vehicles' actual flight conditions. Therefore, flight demonstrators are being developed by the United States, the Soviet Union, Germany, and Japan as "flying test beds" to validate the required technologies at speeds between Mach 8 and 25.

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### Computational Fluid Dynamics

Although European aerospace vehicle programs depend heavily on numerical aerodynamic simulation, they still rely on wind tunnels to validate new designs, refine design configurations, establish data bases, and validate computational fluid dynamics simulations. For example, the European Space Agency plans to utilize European hypersonic wind tunnels for up to 2,000 days between 1986 and 1993 for its Hermes spaceplane project. Fundamental research in hypersonics for HOTOL, Saenger II, and other aerospace vehicle concept and system studies will also rely heavily on European hypersonic wind tunnels and instrumentation.

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### Requirements for Hypersonic Flow Simulation and Research

According to the Director of the von Karman Institute for Fluid Dynamics, the requirements for conducting hypersonic flow simulation and research in hypersonic test facilities in Europe include the following:

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<sup>1</sup>Construction of the Rocketdyne Hypersonic Flow Laboratory shock tunnel has stopped due to a reevaluation of the contractor team, escalating costs, and the availability of other test facilities. Although some of the components were built, there are no plans at this time to complete the facility.

- Model lengths should be at least 30 centimeters long for development testing to provide ample instrumentation. Final configuration tests may require models that are at least 50 centimeters long. If high-incidence testing is necessary at speeds greater than Mach 6, then the nozzle diameter may need to be twice the model length to avoid wall or shear layer interference effects. Facilities that have nozzle diameters between 0.5 and 1 meter and operate at the proper Mach number and Reynolds Number will be required. Smaller European hypersonic wind tunnels will still play a vital role in providing, at modest cost, basic research results, initial design testing, test conditions for developing instrumentation, and training.
- The running time of the facility should be 5 milliseconds per meter. Thus, if the factor of two for the ratio of nozzle diameter to model length is used, then 1-meter facilities should have a running time of at least 10 milliseconds.
- Limitations on internal balances in terms of response times must be considered, since force measurements constitute an important aspect of design work. Recent developments at the Rheinland-Westfalia Technical University at Aachen, Germany, and the von Karman Institute for Fluid Dynamics at Rhode Saint Genese, Belgium, have demonstrated that response times can be as short as a few milliseconds using inertially compensated systems.
- Accurate and detailed dynamic stability measurements with large complex models (e.g., with moveable flaps) will require even longer testing times, probably up to a minimum of several seconds.
- Quiet wind tunnels are required for an accurate determination of transition location.
- Instrumentation of a non-intrusive nature is required for computational fluid dynamics code validation, and the accuracy and reliability for instrumentation to measure heat flux and forces and moments must be improved.
- Trained personnel, including engineers, scientists, and technicians, must be available. The most productive wind tunnels are those that are supported by an instrumentation branch and have a team that has been working together for several years. Experience in running facilities; in selecting appropriate measurement techniques that are compatible with data needs, tunnel characteristics, and data acquisition systems; and in developing new measurement techniques cannot be bought; it must be developed in-house at the facility installation and systematically utilized.

## Characteristics of European Hypersonic Wind Tunnels

Although existing renovated European hypersonic facilities play a major role in the European Space Agency's Hermes spaceplane program, new facilities will be required to adequately design and build post-Hermes aerospace vehicles. The Director of the von Karman Institute for Fluid Dynamics believes that emphasis should be placed on the following facilities:

- a large blowdown facility with a nozzle that has a diameter greater than 2 meters, Mach number of 8 to 10, reservoir pressures up to 200 bars, and a running time of 10 seconds for detailed configuration testing;
- a high velocity shock tunnel based on the Stalker tube concept;<sup>2</sup> and
- a real gas facility similar to the National Aeronautics and Space Administration Langley Research Center's CF4 wind tunnel to simulate certain blunt body and high-incidence effects.

The Director believes that high-quality tunnel flows and accurate, non-intrusive instrumentation capabilities will become increasingly important to validate computational fluid dynamic codes for future hypersonic lifting body designs. According to the Director, efforts should continue to develop quieter hypersonic tunnels to better duplicate boundary layer transition.

Between 1986 and 1990, the National Office for Aerospace Studies and Research and the German Aerospace Research Establishment have established a strong program to develop instrumentation to measure local species concentrations and temperatures at high-flow speed in short-duration facilities. Specific instruments that result from this program will be installed in the F4 Hotshot and High-Enthalpy Tunnel facilities. Finally, even though the lack of adequately trained wind tunnel engineers, scientists, and technicians may have been the most acute problem in 1986, the Director believes this is no longer a problem due to the many new programs now underway in European research institutes and universities.

Aerospatiale officials told us that a 5-megawatt, low-pressure arc facility was being built at Aerospatiale's facility in Bordeaux, France, and was scheduled to become operational in 1989. The tunnel was being expanded to test temperatures and static skin pressures for Hermes. Aerospatiale's 20-megawatt arc plasma high-pressure material test

<sup>2</sup>This requirement for a new facility has been met by construction of the German Aerospace Research Establishment's Goettingen High-Enthalpy Tunnel, which is expected to become operational in 1991.

facility has been operational for more than 20 years. Aerospatiale officials said data reliability is a problem and expressed concerns about obtaining accurate test data from wind tunnel facilities in France and Germany. One official said that he is not as optimistic as National Office for Aerospace Studies and Research officials about obtaining accurate data from the F4 Hotshot Wind Tunnel, since it may take from 6 months to 6 years to get good test data from new wind tunnels. According to the Office, it has never experienced that long of a period in time in obtaining good test data from its new wind tunnels. Aerospatiale officials said test data are reliable in the R2Ch Blowdown Wind Tunnel (built in 1960) and the R3Ch Blowdown Wind Tunnel (built in 1963). Each of these tunnels have conducted thousands of tests over the past 30 years.

Avions Marcel Dassault-Breguet Aviation officials said that they use the CALSPAN shock tunnels at the Cornell Aeronautical Laboratory in Buffalo, New York, and The Australian National University T-3 Shock Tunnel in Canberra, Australia, to check their quality and have a basis for comparison with the 19 European wind tunnels the company uses to test Hermes.

French space agency officials said there would be a need to build new facilities to test air-breathing propulsion, since the current facilities in Europe are small. Despite the possible shortcomings of the F4 Hotshot Wind Tunnel, National Office for Aerospace Studies and Research officials have not identified the additional facilities needed. They did indicate that the Office would like to have a facility similar to the F4 Hotshot for ramjet propulsion with a two-dimensional air-intake flow rather than a circular flow system. Currently, there are no plans to build big facilities to test engines. Office officials added that facilities do not exist in Europe for testing ramjets and scramjets.

According to the U.S. Air Force Foreign Technology Division, European needs for propulsion test facilities may be considerably less demanding than U.S. needs. European countries may be able to develop their air-breathing aerospace vehicle concepts with existing facilities, since European vehicles are not designed to travel much beyond Mach 7. The NASP Program's scramjet, on the other hand, is being developed to achieve speeds of up to Mach 25. According to the Foreign Technology Division, European aerospace vehicle programs may also benefit from the availability of Soviet wind tunnel facilities, which would likely fill any ground testing gaps that the European countries might have. In fact, the shortfalls identified in European facilities correspond to the strengths of major Soviet facilities.

European hypersonic facilities are generally smaller than U.S. hypersonic facilities. Most European facilities are operated by a team of two to six staff members (such as engineers, scientists, and technicians), whereas in the United States much larger project teams are common. U.S. teams usually consist of staff members that specialize in a specific aspect of the test (e.g., instrumentation, data reduction, flow visualization, or data analysis). The difference in the number and type of staff is due to the fact that U.S. wind tunnels are used primarily for system development tests that require a high throughput rate (requiring larger and more specialized staff) and are not used for fundamental research, which is accomplished at a much slower pace.

In general, the Europeans emphasize basic research, fundamental concepts, numerical analysis code verification, and small research facilities, whereas the United States emphasizes system development through full-scale design verification and development testing in large and expensive facilities. In addition to differences in physical dimensions and capabilities of European and U.S. hypersonic wind tunnels, the types of tests being conducted in European facilities is an important indicator of not only their capabilities but also of their intentions.<sup>3</sup>

According to senior U.S. hypersonic researchers, Europeans are making important progress, since they have the building block technologies to make the hypersonic wind tunnel facilities valuable. For example, data acquisition instrumentation (not any specific piece of equipment, but rather the basics of instrumentation) is well developed in Europe. Computers for data reduction are universally available in Europe, and European researchers are using the latest technologies.

European researchers are also developing a strong technical foundation based on in-depth research into fundamental hypersonic flow physics. U.S. researchers with years of first-hand experience in hypersonics and knowledge of European hypersonic capabilities have been impressed by the dedication, perseverance, and hard work of these European researchers.

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<sup>3</sup>Specific examples of the types of tests and applications of European hypersonic and hypervelocity wind tunnels are discussed in our report on foreign test facilities. That report provides technical data and information on principal European wind tunnels and air-breathing propulsion test cells, including performance characteristics (i.e., technical parameters describing the facility's principal capabilities and operating range), cost information, and the number and type of staff required to operate the facility. This catalog of foreign aerospace test facilities also provides narrative information describing each facility, its testing capabilities, data acquisition capabilities and equipment, planned improvements, unique characteristics, and current programs.

The Director of the von Karman Institute for Fluid Dynamics noted that any assessment of European strengths and weaknesses in hypersonic technology must consider that Hermes will be the first lifting reentry vehicle developed in Europe, whereas the United States has had three decades of experience with a variety of both manned and unmanned vehicles. For this reason, the United States has a substantial lead over Europe in experiencing, understanding, and resolving the engineering problems associated with hypersonic flight. However, the United States does not have a substantial lead over Europe in the fundamental tools required for hypersonics: computers, wind tunnels, and knowledge. Also, the rate of progress in Europe during the last few years in the field of hypersonics has been exceptionally high.

The Europeans are making a determined effort to challenge U.S. superiority in hypersonics. However, the United States is ahead in terms of facility size, productivity, and use of testing techniques. Nonetheless, U.S. hypersonic wind tunnel facilities are typically 25 to 30 years old, and the Europeans are making rapid progress in improving and developing new hypersonic test facilities. The Europeans' rate of progress in refurbishing and modifying old facilities and in building new facilities is significantly greater than that of the United States.

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## Advanced Materials Research, Development, Production, and Fabrication Laboratories

A key indicator of foreign countries' capability to develop and build an air-breathing aerospace vehicle is whether they can develop and produce large quantities of high-strength and lightweight materials that are able to withstand high temperatures and are fully reusable. Also, component fabrication and testing, as well as joining technology for advanced materials, are important indicators of foreign countries' ability to build a spaceplane.

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### France

The National Office for Aerospace Studies and Research's Materials Department in Chatillon, France, conducts materials research and development for spaceplane applications in intermetallics (mainly titanium and nickel-based alloys); high-temperature ceramic-ceramic composites (i.e., carbon and silicon carbide fiber-reinforced matrix that consists mainly of carbon, silicon carbide, or silicon nitride, oxides, and glass ceramic); and other kinds of composites (such as metallic and resin matrix). Work conducted in nonstructural materials such as seals and joining technology is currently restricted to more conventional materials

such as nickel-based superalloys under the form of felts or rapid solidification technology-processed honeycomb structures. The joining activity concerns essentially the diffusion brazing of superalloys. Research, however, is carried out in oxidation protection (coatings) of both metallic alloys (superalloys and titanium alloys) and some ceramic-ceramic composites.

In material manufacturing and testing technology, the National Office for Aerospace Studies and Research's main facility consists of casting and rapid solidification technology devices for metallic alloys, processing lines to manufacture ceramic matrix composites, and mechanical testing of materials at high temperatures. In thermal control technology, the Office's facility is not involved in, for example, active cooling (a heat transfer system that transports and dissipates tremendous heat loads over large areas such as a wing or the fuselage) or platelet technology.

The Office's Materials Department staff has 165 employees (including 40 doctoral candidates). About 35 of these employees (20 scientists and engineers and 15 technicians) are involved in research activities related to space vehicle applications.

The facility's testing capabilities include both a 2- and 15-kilowatt continuous heat source and wind tunnel. It also has oxidation test equipment. The facility's manufacturing capability includes a production capacity of about 200 pounds per year of rapid solidification technology-processed ti-aluminide. The facility does not produce any hydrogen-compatible materials that could be used in a spaceplane's cryogenic fuel tank.

Industry facilities include Aerospatiale's and the European Propulsion Company's new facilities to test protection systems and manufacture materials for Hermes. These facilities have carbon-carbon and silicon carbon manufacturing capability.

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## **The Netherlands**

The National Aerospace Laboratory's Structures and Materials Division conducts tests of aluminum alloys, adhesive bonding, composite materials, and engines. Its laboratories are involved in stress and deformation measurements, nondestructive inspections, fatigue testing techniques, and quality assurance. Aerospace candidate materials can be evaluated and compared by a flight simulation loading fatigue machine. A high-

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temperature test installation can conduct tests up to 1,500 degrees Centigrade. Most materials tested by the Laboratory are purchased in France and Germany, since few Dutch companies manufacture materials. However, one Dutch company makes composites from fiber-reinforced aluminum laminate. According to a Laboratory official, a recent study of crack propagation at high temperatures has applications for engines and future hypersonic vehicles.

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## Supercomputer Facilities

Computational fluid dynamics research is accomplished using high-speed digital computers known as supercomputers. The U.S.-manufactured Cray 2, for example, considered to be the world's fastest and most powerful computer, can perform 250 million continuous calculations per second.

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### France

According to information the National Office for Aerospace Studies and Research had in September 1988, France had about 18 supercomputers, including 15 Crays, 2 ETAs, and 1 Fujitsu. The Office shares its Cray XMP-18 supercomputer with industry (primarily Avions Marcel Dassault-Breguet Aviation and Aerospatiale). The Office also has access to a Cray 2 supercomputer installed at the Ecole Polytechnique, or Polytechnical School, in Palaiseau, France. Aerospatiale has a Cray XMP-14SE supercomputer in Toulouse, according to Office officials. The officials also said about four or five supercomputers are used for computational fluid dynamics work in hypersonics and that they expect such usage to increase.

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### Germany

According to the Federal Ministry for Research and Technology, supercomputers available in Germany include a Cray 2 supercomputer at the University of Stuttgart and a VP 200 supercomputer at Messerschmitt-Boelkow-Blohm. Even though these systems can do analytical simulations of flow fields, thermodynamic effects, and gas kinetics in about 300 to 500 hours, the Ministry would like to increase available computer power and memory space to better facilitate research for the Hypersonic Technology Program. According to the Ministry, a high computer power is needed for the design of Saenger II's propulsion system.

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### United Kingdom

According to the Director of the Oxford University Computing Laboratory and Institute for Computational Fluid Dynamics, supercomputers

available in the United Kingdom include a Cray 1-S, Cray 2, and an ETA 10. Organizations with supercomputer capabilities include the Royal Aerospace Establishment at Farnborough, Rolls-Royce, British Aerospace, Aircraft Research Association Bedford, Oxford University, the University of Manchester, and the Institute of Technology. Even though supercomputers are available, a British National Space Centre official told us that software must be developed to do more advanced computer modeling, especially computational aerodynamics. A university professor also cited the need for more computer modeling. In addition, the Director of the Oxford University Computing Laboratory and Institute for Computational Fluid Dynamics said that supercomputers are needed to perform three-dimensional flow analysis for such aerospace vehicles as Hermes, Saenger II, and HOTOL.

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## Italy

Italy has several supercomputers, according to an Italian Space Agency official. Currently, supercomputers are located in Rome at the Italian Energy Agency; at the Universities of Bologna, Pisa, and Naples; and in Turin at Aeritalia. The Italian Aerospace Research Center also plans to purchase a Cray YMP supercomputer for its new research center in Capua. The Center currently has an ETA 10 supercomputer. The Center and Italian universities are discussing their supercomputer requirements with Italy's National Research Council.

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## European Facilities Needed for Testing Future Aerospace Vehicles

Europe has already built or is building most of the test facilities it needs for its current aerospace goals and objectives, according to the Director of the von Karman Institute for Fluid Dynamics. The Director said the planned Hermes facilities in Germany and France will increase Europe's capability to perform more advanced hypersonic testing. European Space Agency and National Center for Space Studies officials said these facilities will be used as much as possible for post-Hermes vehicles.

French industry officials, however, expressed doubts about European facilities. For example, an Aerospatiale official stated that he is not optimistic about how and when the planned F-4 Hotshot Wind Tunnel for testing Hermes at the National Office for Aerospace Studies and Research's Le Fauga-Mauzac Centre in Noe will deliver accurate data. The official said accuracy and reliability have to be established for new facilities. In addition, an Avions Marcel Dassault-Breguet Aviation official said European facilities are not adequate for any aerospace vehicle, including Hermes. However, according to the Office, the work done on

new flow diagnostic techniques will allow reliable and accurate results within the F4 Hotshot Wind Tunnel.

European officials said that some additional facilities are needed to test a vehicle beyond Hermes. For example, European Space Agency officials said hypersonic wind tunnels and air-breathing test cells are needed. National Office for Aerospace Studies and Research officials stated that facilities do not exist in Europe for testing scramjets and that facilities are lacking for testing materials and structures. In addition, the National Center for Space Studies and Aerospatiale officials cited the need for a flight demonstrator. The European Space Agency does not plan to build new facilities for a post-Hermes vehicle at this time.

Messerschmitt-Boelkow-Blohm officials said German facilities are adequate for testing concepts but not for testing vehicles. Federal Ministry for Research and Technology and German industry officials stated that either new facilities must be built or existing facilities must be modernized to test future air-breathing aerospace vehicles. According to the Ministry, specific shortfalls relate to wind tunnels, engine facilities, and supercomputers. The Ministry is considering whether to build new facilities, modify existing facilities, or utilize facilities in other countries.

British government and industry officials cited the need for new or improved engine test facilities. According to the Director of the Oxford University Computing Laboratory and Institute for Computational Fluid Dynamics, a number of supercomputers are available in the United Kingdom for aerospace vehicle simulation; however, improvements in supercomputer capability are needed.

Italian Space Agency and Italian Aerospace Research Center officials stated that Italy does not have adequate aerospace test facilities. Some of Italy's wind tunnels are mothballed<sup>4</sup> or decommissioned,<sup>5</sup> forcing industry to go outside of Italy for wind tunnel testing. To assist Italy's aerospace industry in becoming more competitive, the Center plans to build a number of test facilities at its center in Capua. An Italian Space

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<sup>4</sup>The facility and plant are intact but not maintained. Protective measures have been taken. Major components have not been removed (i.e., the basic test capability has been preserved). Minor components and instrumentation may have been removed for storage or use elsewhere. Testing can be resumed only after considerable refurbishment and/or modification.

<sup>5</sup>The facility and plant are not maintained. Major components have been removed for storage or use elsewhere, so the integrity of the facility may not have been preserved. Reactivation is possible but would be a major undertaking and considered only if a unique potential capability exists.

Agency official stated that the agency will provide about \$575 million for the facilities. Fiat Aviazione also plans to build new test facilities.

The Italian Aerospace Research Center plans to build several new wind tunnels, including the Low-Speed Wind Tunnel, High Reynolds Transonic Wind Tunnel, and a transonic extension to the Low-Speed Wind Tunnel. The Italian Space Agency is providing about \$46 million for the Low-Speed Wind Tunnel and about \$92 million for the High Reynolds Transonic Wind Tunnel. The transonic extension to the Low-Speed Wind Tunnel, which has not yet been funded, will cost about \$23 million.

In addition, according to Italian Space Agency and Italian Aerospace Research Center officials, the Center is planning to build a 70-megawatt, continuous-flow, electric arc-heated hypersonic wind tunnel with Mach 3.5 and 5 nozzles that will be jointly funded by the Italian government and the European Space Agency. The primary purpose of the planned Plasma Wind Tunnel is to study and qualify parts of the thermal protection system for the reentry phase of Hermes. The tunnel is expected to cost about \$53.7 million. The Agency will provide about \$23 million of this amount and the European Space Agency will provide about \$30.7 million of this amount. The Italian Aerospace Research Center has not received final approval yet for the tunnel.

In addition to wind tunnels, the Italian Aerospace Research Center plans to build other facilities in Capua, including a building to house the supercomputer, technical laboratories, administrative bays, and an electrical plant. The Italian government provided a total of about \$575 million to fund the facilities necessary to provide the Center with partial operational capability in 1989.

Fiat Aviazione submitted a proposal to the Italian Space Agency to build an engine test facility to test liquid oxygen, liquid hydrogen, and eventually liquid nitrogen turbo pumps.<sup>6</sup> This facility, which would be a backup to a similar facility at Messerschmitt-Boelkow-Blohm in Ottobrunn, Germany, will be used for Ariane 5 testing. Although the facility would not be a complete testing facility for all air-breathing engine work, it could be used for development testing of cryogenic engines and capability testing of air-breathing engine components. The total cost of the facility is about \$61.3 million. The first phase will cost

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<sup>6</sup>National Aeronautics and Space Administration officials doubt that anyone will ever test liquid nitrogen turbo pumps.

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about \$46 million, and Fiat officials hope the Agency will fund half of this amount. Fiat hopes to build the facility by 1995.

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# International Cooperation

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European governments and industries cooperate extensively on the European Space Agency's Hermes and Ariane 5 programs. European industries also cooperate on generic European Space Agency hypersonic and propulsion studies. However, most European governments are not participating with other governments on air-breathing aerospace vehicle research and technological development efforts, since they want to develop a vehicle concept first, on a national basis, before seeking international partners or making a proposal to the European Space Agency. Industry-to-industry cooperation in Europe on air-breathing aerospace vehicle research and technological development efforts is widespread.

European government officials and industry representatives expressed interest in cooperating with the United States on the NASP Program, but they also expressed reservations about cooperative ventures with the United States. According to U.S. government and industry officials, areas in which European technology might be incorporated in the NASP Program include advanced propulsion and advanced materials. Key European test facilities could also be used by the NASP Program.

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## Cooperation Within Europe

France's National Center for Space Studies is not participating with other governments on air-breathing aerospace vehicle research and development efforts. Center officials said they want to reach a consensus on an advanced system before approaching other countries regarding a cooperative venture. They also do not favor European Space Agency involvement at this time. The officials added that this does not prevent normal industry-to-industry talks. For example, the National Company for the Study and Construction of Aviation Engines and the European Propulsion Company participated in a preliminary European Space Agency study on air-breathing vehicles.

Germany also is not participating with other governments on air-breathing aerospace vehicle research and development efforts. According to its Federal Ministry for Research and Technology officials, Germany wants to study and develop a vehicle concept first, on a national basis, before cooperating with other countries. Ministry officials explained that this is why Phase I of the Hypersonic Technology Program will be a national effort. Once Phase I is completed, the Ministry plans to propose a vehicle concept to the European Space Agency to be developed under Phases II and III.

German industry cooperates with other European companies within the European Space Agency, according to industry officials. European Space

Agency studies on hypersonics were carried out by Messerschmitt-Boelkow-Blohm and British Aerospace as well as by Rolls-Royce, Motoren- und Turbinen-Union, and Fiat Aviazione.

Between June 1989 and May 1990, German government and Messerschmitt-Boelkow-Blohm officials made presentations on efforts to develop Saenger II to European Space Agency officials at the Agency's Headquarters and to government officials (plus invited research institute and industry representatives) in those countries that had expressed interest in cooperation on Saenger II. The countries were the United Kingdom, Spain, Norway, Italy, The Netherlands, Sweden, Austria, Belgium, Switzerland, and Canada. These visits were made to establish European Space Agency, European, and Canadian participation in the Saenger II technology development phase, obtain immediate research support, and secure eventual international participation in the HYTEX demonstrator vehicle. Officials in these countries are determining their specific contributions to the German program. Cooperation with Australia has also been initiated. In 1990, Messerschmitt-Boelkow-Blohm officials made formal presentations to government officials, industry representatives, and university researchers in Australia. Their visit was to determine opportunities for collaboration, coordinate potential activities in Australia with the Saenger II program, and explain Germany's future space transportation systems' goals and activities.

In September 1990 a memorandum of understanding was signed between Germany's Federal Ministry for Research and Technology and the Swedish National Space Board in which Sweden agreed to cooperate with Germany on the Saenger II program through an exchange of information. According to a Swedish National Space Board official, Sweden plans to spend about \$5.4 million between 1990 and 1992 on Saenger II-related hypersonic work. Funding for the Swedish Technology Program-Saenger is coordinated through the Swedish Space Corporation in Solna, Sweden, on behalf of the Swedish National Space Board. Volvo Flygmotor in Trollhattan, Sweden, is concentrating on hypersonic aerodynamics, hydrogen combustion, and secondary power systems. Saab-Scania Combitech and Saab Space in Goteborg, Sweden, are working on engine design. Saab-Scania in Linkoping, Sweden, is working on computational fluid dynamics of flap efficiency and applied aerodynamics studies. The Flytekniska Forsoksanstalten, or Aeronautical Research Institute of Technology, in Stockholm, Sweden, is concentrating on control and stability, flap efficiency, studies of hypersonic transition from laminar flow to turbulent flow, and on computational fluid dynamics.

A similar research sharing agreement for work on Saenger II through 1992 for about the same amount was signed in December 1990 between Germany's Federal Ministry for Research and Technology and the Norsk Romsenter, or Norwegian Space Center, in Oslo, Norway. Raufoss in Raufoss, Norway, is developing oxide dispersion- strengthened materials, metal matrix composites, and rapidly solidifying aluminum. Computational Fluid Dynamics Norway in Trondheim, Norway, has reached an agreement with Messerschmitt-Boelkow-Blohm for numerical aerodynamic simulation work on Saenger II.

Although company-to-company agreements have already been signed between Messerschmitt-Boelkow-Blohm, Aeritalia, and Fiat Aviazione, a government-to-government agreement is needed between Germany and Italy. In January 1991 the Secretary of State of the Italian Ministry for Universities and Scientific and Technical Research announced that Italy could participate in Phase I of Germany's Hypersonic Technology Program. However, this commitment is contingent upon satisfactory participation in the program by Italian industry. The Italian and German research ministries are expected to sign a memorandum of understanding in 1991 for a 15- to 20-percent Italian participation in the Saenger II project. This level of participation would represent an Italian investment of \$36 million to \$48 million between 1991 and 1992. According to Italian officials, Italy will support Saenger II on a bilateral basis only if the project will not force a drastic reduction of German space activities in the European Space Agency due to the cost of German reunification.

None of these governments is providing funds directly to Germany. Instead, the governments have agreed to pursue complementary technologies for hypersonic vehicles in cooperation with the German government. The work will be conducted by local industries within these countries.

Messerschmitt-Boelkow-Blohm's Director of Advanced Space Transportation Systems told us that development of the Saenger II technology demonstrator vehicle depends on France, since Germany could not develop and build HYTEX alone. Discussions are ongoing between Messerschmitt-Boelkow-Blohm and the Hyperspace consortium in France.

Although Saenger II may eventually be a European effort, German officials caution that the project is still in its beginning and is not ready to be formally presented to the European Space Agency. According to the

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Federal Ministry for Research and Technology's Director of Aeronautical and Spaceflight Technologies, Germany's policy is that Phase II development of Saenger II should be done with European cooperation, preferably within the European Space Agency.

Discussions between Daimler Benz (Deutsche Aerospace's parent company) and Mitsubishi Heavy Industries of Nagoya, Japan, are continuing regarding possible Japanese cooperation on Saenger II. As of November 1990, Mitsubishi had made no formal decision to participate on the Saenger II program. Representatives from Messerschmitt-Boelkow-Blohm planned to visit the Soviet Union in May 1991 to brief Soviet officials on Saenger II and to solicit Soviet participation in the program.

According to the Director-General of the German Space Agency, German negotiations with individual countries on spaceplane development might be a necessary intermediate step before Saenger II is fully adopted as a European program. The Director-General said that Saenger II is too large an undertaking for just one country but is not ready to be taken over by the European Space Agency, so bilateral cooperation may be what is needed. The Director-General added that the current budget for Saenger II investment is not enough to finance a demonstrator model. According to a Messerschmitt-Boelkow-Blohm official, the company will not insist on a lead role in developing Saenger II but wants a consortium on Saenger II similar to the Eurofighter or Airbus consortiums to be established.

According to British National Space Centre officials, the Centre is not participating with other governments in the research and development of an air-breathing, hypersonic aerospace vehicle. However, according to Centre officials, the agency is exploring opportunities for international collaboration for future research activities needed to develop HOTOL. A British Aerospace official said that the company is also seeking international partners. According to the British Parliamentary Undersecretary of State for Trade and Industry, the British government fully supports British Aerospace's attempt to seek international partners, and the government might reconsider funding for HOTOL if international partners are found. A Rolls-Royce official said that the likely approach to seeking cooperation will be to look for partners in other British companies first, then in other European countries, the United States, and Japan, in that order.

The British government's decision not to provide funding for HOTOL has stymied British Aerospace's efforts to line up European partners.

According to a British Aerospace official, no other European partner is prepared to provide any funding for HOTOL unless the British government helps. The European Space Agency is not interested, since the British Ministry of Defence has classified the engine technology. The Agency reportedly will not take the HOTOL project seriously without access to HOTOL's engine work. The Agency's disinterest in HOTOL is not entirely based on its inability to gain access to HOTOL's engine technology. The Agency is unable to commit funds to a new aerospace vehicle until the Ariane 5 development program is completed. Thus, the Agency is unlikely to pursue a hypersonic research program until the mid-1990s, at the earliest.

According to industry officials, British Aerospace and Rolls-Royce have participated in European Space Agency studies with other European countries. In 1987 British Aerospace participated in a European Space Agency study to define an advanced technology for liquid propellant rocket engines for future space vehicle applications. In addition, Rolls-Royce, along with Messerschmitt-Boelkow-Blohm and Fiat Aviazione, studied single-state-to-orbit propulsion system integration during late 1988 and early 1989.

A British Aerospace official told us that company officials have met with representatives from other European countries to discuss collaborating on HOTOL technologies. The official said that one partner—the University of Trondheim in Norway—has already been recruited for supercomputer work. In addition, the official told us that British Aerospace is encouraging involvement from The Netherlands and Italy.

Italian industry has cooperated in several aerospace vehicle programs within the European Space Agency. For example, Fiat Aviazione and Bomprini Parodi Delfino—National Industrial Applications Corporation participated with the National Company for the Study and Construction of Aviation Engines and the European Propulsion Company in a European Space Agency study on Europe's testing capabilities and air-breathing research problems, according to a Bomprini Parodi Delfino—National Industrial Applications Corporation official. In addition, the Italian Space Agency is exploring cooperation between Fiat Aviazione, Aeritalia, and German aerospace companies on Saenger II system studies. An Agency official described this as a joint industrial venture. The official said the proposed collaboration is under discussion with German officials, but no decision had yet been reached, since Germany is reluctant to share its technology.

The Italian Aerospace Research Center began exchanging computational fluid dynamics codes in 1988 with The Netherlands' National Aerospace Laboratory. According to the Center, to cooperate with international partners, it must be able to operate at the same level in terms of quantity and quality as its international partners. Center officials believe that the Italian aerospace community has a great deal to learn in several fields before it is able to make international contributions.

Netherlands Institute for Aerospace Programs and National Aerospace Laboratory officials cited the German-Dutch Low-Speed Wind Tunnel as an example of successful cooperation in Europe. The tunnel's construction, operation, and further development are conducted equally by the National Aerospace Laboratory and the German Aerospace Research Establishment. Any European cooperation by The Netherlands would probably be under the European Space Agency.

Belgian aerospace companies have worked closely with other European companies in European Space Agency space-related research and development activities. U.S. Embassy officials were unaware of any Belgian cooperation with the United States, Soviet Union, or Japan in air-breathing aerospace vehicle research and development.

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## U.S./European Cooperation

Although the United States continually assesses the possibility and desirability of international cooperation in developing and building the X-30, NASP Program officials have not developed a formal strategy or written policy regarding international collaboration. NASP Program officials have not actively sought international cooperation. However, in September 1988 the NASP Program Director stated that program officials have begun exploring collaboration with foreign countries and that it is very clear the United States is in the lead in technology. Also, in September 1988 NASP Program officials met with representatives from British Aerospace and Rolls-Royce to discuss access to data collected on HOTOL's airframe and propulsion systems.

In September and October 1988, members from the NASP Joint Program Office Fact Finding Group representing the NASP Joint Program Office, Office of Science and Technology Policy, McDonnell Douglas Corporation, and Rockwell International Corporation visited France, Germany, the United Kingdom, and Japan to (1) exchange information about the status and plans for spaceplane development in Europe, Japan, and the United States; (2) understand the problems and technical barriers to

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spaceplane development; and (3) explore specific technical areas for possible use on NASP or for possible collaborative development.

After these visits, the NASP Program Director ruled out joint development of the X-30 with any one country. Currently, no discussions are being held on international collaboration for designing and developing the X-30. U.S. officials believe that the United States is ahead in developing enabling hypersonic technologies, some of which may have significant commercial applications in the future. The Acting Director of the Office of Science and Technology Policy stated in July 1989 that any sharing of technology will be judged on how the technology would benefit the parties, not on whether the technology would reduce costs. The National Space Council considered the possibility of international cooperation on the NASP Program, but most council members believe NASP should remain a national program, since aerospace technology is one of the few remaining areas in which the United States has a positive balance of trade (about \$26.9 billion in 1990 and an estimated \$37.1 billion in 1991, according to the Department of Commerce). As of July 1991, the NASP Program Director did not anticipate that the NASP Program would seek international partners.

The National Aeronautics and Space Administration has frequent contacts with foreign aerospace vehicle program managers, scientists, and engineers. It utilizes foreign expertise and monitors foreign programs through existing data exchange agreements.

NASP airframe contractors do not favor international cooperation. They believe that the United States is far ahead in hypersonics and that Europe and Japan would have little to offer. However, some subcontracting with European companies has occurred through traditional partnerships. According to a U.S. expert on hypersonics, as European industries look for ways to cooperate with each other, they would also like to find ways to cooperate with U.S. industry. If U.S. government funding for the NASP Program diminishes, then U.S. industry may reconsider seeking foreign support, according to U.S. industry representatives. Germany and Japan are considered the most probable possibilities by U.S. industry, since their commitment to hypersonic programs appears strong. The United Kingdom's commitment is viewed as weak because of the British government's decision in July 1988 not to fund HOTOL research any longer. If U.S. government funding for NASP diminishes, U.S. industry officials are concerned that any collaborative agreement may be difficult to achieve because of U.S. export controls on the transfer of technology.

According to U.S. and foreign government officials and industry representatives, advantages of international cooperation in the NASP Program include sharing technical data and information, expertise, and approaches; having access to greater resources such as test facilities; sharing costs; reducing or eliminating duplication; and increasing the market size. Disadvantages include inherent difficulties in different program goals and objectives, concepts, and size; sharing technology; sharing ownership; difficulties in integrating diverse national bureaucracies; delays in reaching decisions due to differing political and legal systems; complications resulting from different decision processes, priorities, and competencies; increased administrative cost; political inertia, which may make projects hard to start and even harder to stop; competition for funding with countries' other national and international commitments; a tendency to undertake low-priority projects only; conflicts between cooperation and competition; and a decreasing market share.

The French space agency and French aerospace companies are not involved with the United States in cooperative research and development efforts on air-breathing aerospace vehicles, according to National Center for Space Studies and industry officials. Center officials stated that the French space agency and the National Aeronautics and Space Administration have discussed collaboration, but nothing has been decided. They believe France and the United States can cooperate, and they said they would be willing to discuss the possibility of a cooperative effort.

An Aerospatiale official said he sees no barriers to cooperation in the development of a commercial hypersonic airplane. The official stated that France cannot develop an aerospace plane by itself and has no objections to cooperation. According to a company official, Avions Marcel Dassault-Breguet Aviation is completely open to international cooperation as long as the cooperation is an equal partnership. National Company for the Study and Construction of Aviation Engines and European Propulsion Company officials believe it is possible to cooperate with the United States on basic technology, but a political decision would be required for cooperation on specific programs.

French officials cited a few specific areas in which they believe cooperation is possible. For example, a National Office for Aerospace Studies and Research official said cooperation with the United States is possible in the field of hypersonics and related instrumentation and in the field of ramjets. Upon request, the Office could participate in a joint analysis of U.S. spaceplane designs. Opportunities also exist for cooperation in

the field of advanced materials. For example, an industry official said three-dimensional weaving is something France can offer the United States. A National Center for Space Studies official noted that France has good scientists in computational fluid dynamics. Further, French aerospace companies can work with companies from other countries without French government approval, the Center official stated.

According to the President and Chairman of the Board of the European Propulsion Company, the French propulsion company would like to cooperate with the United States on NASP, but French officials are concerned about excessive U.S. technology transfer restrictions. U.S. officials said European Propulsion Company ceramic and carbon-carbon technology would be valuable to the NASP Program.

According to Federal Ministry for Research and Technology and industry officials, Germany is not participating with the United States in conducting research or developing air-breathing aerospace vehicles but would be interested in future cooperation. For example, Motoren- und Turbinen-Union officials told us that their company would like to participate in the NASP Program under a data exchange agreement allowing for full partnership and full access to data. They said a government-to-government memorandum of understanding is probably not required for such cooperation. The Motoren- und Turbinen-Union officials further stated that it is easier to cooperate on basic technology than on development programs. Data exchange agreements, the use of test facilities, and heat exchange were mentioned as opportunities for cooperation.

Messerschmitt-Boelkow-Blohm has contacted several U.S. companies (McDonnell Douglas Corporation, Rockwell International Corporation, and United Technologies Corporation) about participating in the construction of the \$2 billion Saenger II subscale flight demonstrator, since individual European countries, at that time, appeared unlikely to participate in the project during the next few years. Discussions have been very general in nature, focusing on the status of the Saenger II program rather than on any detailed proposals.

Because the United Kingdom is seeking international partners for HOTOL, British National Space Centre and industry officials told us that they would be interested in cooperating with the United States. Centre officials told us that the Centre is exploring prospects with the United

States at two levels. At the government level, Centre and industry officials made presentations to the National Aeronautics and Space Administration, Defense Advanced Research Projects Agency, and U.S. Air Force. At the industry level, the Centre and industry are considering collaboration with several U.S. companies. According to Centre officials, specific opportunities for cooperation include exchange of technical information (especially work in cryogenic fuel tanks) and use of special equipment needed for engine research.

In the past, NASP propulsion scientists and engineers were interested in learning the process of HOTOL's RB-545 combined-cycle engine concept. The U.S. and British governments allowed NASP Program managers and British Aerospace representatives to exchange classified X-30 and HOTOL hypersonic propulsion system data. However, after the exchange of engine data, British Aerospace officials were reportedly less interested in cooperating with the United States. Nonetheless, U.S. officials wanted to explore working with British Aerospace further. Over time, U.S. interest in HOTOL's combined-cycle engine concept eventually diminished. Rolls-Royce also has air-breathing propulsion experience that would be useful to NASP's low-speed propulsion requirements, according to U.S. officials. British Petroleum is also interested in participating in NASP technology development efforts.

NASP contractors have also sought international cooperation with British Aerospace and Rolls-Royce. Representatives of Pratt & Whitney and Rocketdyne, the two NASP propulsion system design contractors, said they have conducted very preliminary discussions on receiving propulsion data from Rolls-Royce. According to the Vice President and General Manager—NASP at McDonnell Douglas Corporation, the company had expressed interest in test facilities used in the HOTOL program.

Technical and scientific exchanges between Italy and the United States in the field of aerospace and visits to National Aeronautics and Space Administration research centers by Italian government and industry officials have been long-standing. Italian Space Agency and Italian Aerospace Research Center officials expressed interest in bilateral agreements or joint ventures with the United States. An Agency official said cooperation is possible as long as the bilateral agreements do not interfere with Italy's responsibilities to the European Space Agency. Center officials said that, although they are interested in joint ventures with the United States, they are not sure what the Italian Aerospace Research Center could offer at this time.

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Dutch government officials said that direct cooperation between The Netherlands and the United States is not realistic, since aerospace research and development efforts in The Netherlands are small compared with those in the United States. However, they added that there would be no significant barriers to cooperation with the United States. These officials suggested using offsets as one way of enhancing cooperation in aerospace activities. They indicated that Dutch test facilities could be used as payment for acquisitions from the United States.

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## Barriers to U.S./European Cooperation

According to National Center for Space Studies officials, the differing levels of effort between U.S. and French programs is a barrier to cooperation. Further, the Center views the NASP program as primarily military, whereas the French program is civil. An industry official said the first hurdle is the lack of a common goal between the European and U.S. programs. The official also cited the difference in the availability of basic technology as a barrier. Some French industry representatives perceive the United States as being reluctant to use European partners.

Barriers to German cooperation with the United States include the military applications of NASP and U.S. export controls associated with transferring technologies. In addition, German Aerospace Research Establishment and industry officials explained that they view the United States as being unwilling to share its technologies.

British National Space Centre officials said the differences in the size of programs and funding are barriers. Further, a British Aerospace official said that although the company is open to cooperation, it is cautious about collaborating with the United States because it does not want HOTOL to be taken over by a larger program.

Officials in the United Kingdom differed in their views on whether the classification of Rolls-Royce's RB-545 engine is a potential barrier to cooperation. For example, the Counselor for Scientific and Technological Affairs at the U.S. Embassy in London said that the British government may be reluctant to share information because the HOTOL propulsion system is classified. In addition, an official of the U.S. Air Force European Office of Aerospace Research and Development told us that classification of the RB-545 engine may be a problem in attracting international collaboration. In contrast, a Rolls-Royce official told us that the classification of the RB-545 engine is not a barrier to cooperation. Further, a British National Space Centre official stated that, despite the engine's classification, the British government has shared

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some propulsion information with North Atlantic Treaty Organization members.

An Italian Space Agency official said Italy has encountered problems in the past in dealing with the United States on technology programs, particularly those having military applications. The official said similar problems may exist in a spaceplane program. Aeritalia officials also said they have experienced difficulty in participating in U.S. programs involving technology sharing and bid competition. They believe U.S. companies do not want to share their programs with foreign companies. A Fiat Aviazione official suggested that the United States may not be interested in international cooperation, since it is ahead in hypersonic technology state of the art.

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### NASP Program's Use of European Test Facilities

Although the NASP Program would benefit from the capabilities of some foreign test facilities, according to the NASP Program Director, no contracts are planned for using foreign test facilities. However, the NASP Program is already using a European test facility for research and development of the X-30. The University of Sheffield Shock Tunnel in Sheffield, United Kingdom, is currently being used to conduct a research program designed to establish high Mach number design criteria that minimize overall combustor loss mechanisms and maximize scramjet performance. The facility is capable of conducting studies of supersonic combustion effects for scramjet operation between Mach 7 and 20. National Aeronautics and Space Administration officials noted, however, that the work is generic in nature and is not an international activity under the NASP Program that requires a government-to-government agreement.

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### European/Soviet Cooperation

Soviet aerospace officials contacted German representatives at the 1989 Paris Air Show about possible Soviet participation in the Saenger II program. The General Designer for the Soviet Ministry of Aviation Industry and Director of the Soviet Central Aero-Hydrodynamics Institute initiated discussions with members of the Messerschmitt-Boelkow-Blohm team that are developing Saenger II. The Soviets would like to share hypersonic technology with the Germans for development of a single-stage-to-orbit space launch vehicle to replace the Buran space shuttle system by 2015. According to the Director of the Central Aero-Hydrodynamics Institute, the costs for the Soviet Union, the United States, Germany, and Japan to develop and build a spaceplane alone will

be too high, which is why cooperation will be inevitable. The Soviet officials were told by German representatives that any cooperation would have to involve a formal government-to-government agreement.

British Aerospace and the Soviet Ministry of Aviation Industry signed a protocol in July 1990 to study the feasibility of air-launching an interim version of HOTOL from the back of the Soviet Union's Antonov An-225 heavy-lift transport aircraft. The 6-month joint study was conducted simultaneously in the United Kingdom and in the Soviet Union, with each organization sharing the data and analyses.

According to the U.S. Air Force Foreign Technology Division, the availability of Soviet wind tunnel facilities may benefit European aerospace vehicle programs. Soviet facilities would likely fill any ground testing gaps that the European countries might have. In fact, the shortfalls identified in European facilities correspond to the strengths of major Soviet facilities. Although barriers exist to European/Soviet cooperation, both sides have a strong motivation to overcome them.

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## International Collaboration Among Foreign Aerospace Plane Programs

Although the United States is ahead of Europe in developing the technologies for an air-breathing single-stage-to-orbit aerospace plane, a significant international collaborative effort in hypersonics involving France, Germany, the United Kingdom, Japan, and/or the Soviet Union could be competitive with the NASP Program. The combined convergence of national interests, expertise, approaches, funding, and sharing of test facilities in such a cooperative effort could, in the long term, seriously challenge U.S. leadership and preeminence in hypersonics.

European countries have been pursuing joint ventures in aeronautics and aerospace for a number of years. To date, cooperation between Europe and Japan has not been significant. According to a National Aeronautics and Space Administration Ames Research Center official, the Soviet Union appears to be aggressively developing joint efforts with European countries. The official said that if the ongoing Interim HOTOL project between British Aerospace and the Soviet Ministry of Aviation Industry is successful, then further Soviet collaboration in hypersonics with European countries and/or Japan may be more likely. This collective capability could serve to quickly erode U.S. leadership in hypersonics in a very short time. The official also noted that the combination of European and Soviet skills, experimental test facilities, and Japanese supercomputers could possibly lead to the development of a European/Soviet aerospace plane that would constitute an awesome

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challenge to the United States. Prospects for international collaboration with the United States are not imminent.

Another National Aeronautics and Space Administration Ames Research Center official said that the Europeans and Japanese will follow whatever decision the United States makes regarding an aerospace plane. If the United States decides to build NASP, then the Europeans and Japanese will immediately initiate a program of their own, probably a collaborative program. The official added that the aerospace plane programs the Europeans and Japanese currently have will allow them to initiate a collaborative program.

# Conclusions

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The United States is ahead of European countries in hypersonic technology. However, U.S. leadership in aeronautics faces increasing competition from European efforts to develop operational aerospace vehicle technologies. No European government or the European Space Agency has officially approved any plan to build a spaceplane. The United States also has not approved a plan to build a spaceplane. However, European countries are conducting feasibility studies and developing the enabling technologies needed for various concepts of operational aerospace vehicles to secure independent manned access to space, reduce the cost of launching payloads into orbit, and ensure a competitive role in future high-speed commercial transport markets.

European aerospace technology development programs are not as technologically challenging as the NASP Program in terms of a single-stage-to-orbit space launch capability and an air-breathing propulsion system using a scramjet. The United States is pushing hypersonic technology the furthest and is the only country that has gone beyond the initial design phases and tested major large-scale components of an air-breathing aerospace vehicle. The United States is ahead of European countries in the development of three enabling technologies considered critical for an aerospace plane: air-breathing propulsion, advanced materials, and computational fluid dynamics. However, European countries are making significant progress in the development of enabling technologies, particularly in advanced air-breathing propulsion and advanced materials. According to U.S. government and industry officials, the NASP Program could benefit from European efforts in advanced propulsion and advanced materials as well as the use of European test facilities.

No European aerospace vehicle program compares to the scope of the NASP Program in terms of the amount of funding or the number and type of people working on the program. Levels of investment in air-breathing aerospace vehicle research and technological development efforts by the European Space Agency and European governments and industries to date are significantly less than U.S. government and industry investment in the NASP Program. Also, planned U.S. government and industry investment in the NASP Program are substantially greater than planned European government and industry investment.

European test facilities (such as wind tunnels and air-breathing propulsion test cells) are adequate for fundamental research and the current level of effort in Europe, but the facilities are not adequate for large-

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scale testing or developing a spaceplane, according to foreign government officials and industry representatives. The Europeans are making a determined effort to challenge U.S. superiority in hypersonics. Although, the United States is ahead in terms of facility size, productivity, and testing techniques, the Europeans are making rapid progress in improving and developing new hypersonic test facilities. The Europeans' rate of progress in refurbishing and modifying old facilities and in building new facilities is significantly greater than that of the United States.

No European country appears likely to develop and build an aerospace plane by itself because of the extensive technology and funding requirements and lack of adequate test facilities. Building a future aerospace plane in Europe will probably be an international effort, most likely under the European Space Agency. European governments want to develop aerospace vehicle concepts first, on a national basis, before seeking international partners or making a proposal to the European Space Agency.

Individually, European countries do not pose a serious challenge to U.S. preeminence in hypersonic aerospace plane technologies. However, the combined convergence of national interests, expertise, approaches, funding, and sharing of test facilities in a major international collaborative effort in hypersonics under the European Space Agency or among European countries, Japan, and/or the Soviet Union, could, in the long term, prove to be competitive with the NASP Program.

European government officials and industry representatives expressed interest in cooperating with the United States on the NASP Program, but they also expressed reservations about cooperative ventures with the United States. Their reservations included past experiences with the United States in other programs (such as the planned U.S. space station), the perception that NASP is a military program, potential military applications of a future NASP-derived operational vehicle, differences in the objectives and size of U.S. and European aerospace plane programs, a reluctance by the United States to share its technology, and strict U.S. export controls on the transfer of technology. Collaborative efforts with the United States on the NASP Program appear unlikely.



# Aerospace Vehicle Programs in Germany

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Although not part of the Federal Ministry for Research and Technology's Hypersonic Technology Program, German industry has conducted low-level conceptual studies on several alternative two-stage-to-orbit space launch vehicle concepts.

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## Messerschmitt-Boelkow-Blohm's Luftatmender Raumtransporter

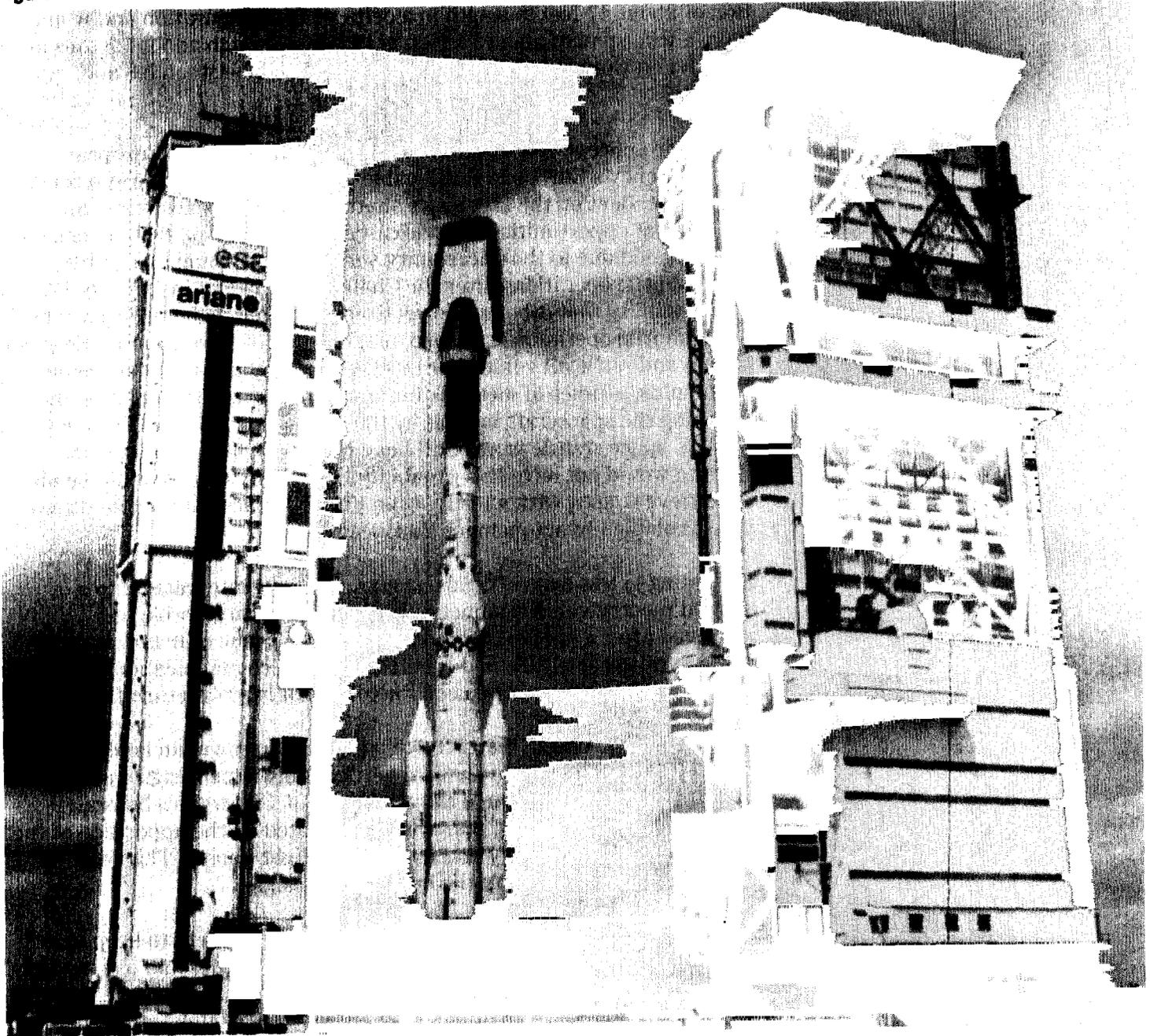
Concerns about the cost of a two-stage-to-orbit aerospace vehicle prompted Germany to reassess a single-stage-to-orbit space launch vehicle known as Luftatmender Raumtransporter (LART), or Air-Breathing Space Transporter. LART is envisioned as an air-breathing rocket-powered vehicle that could be launched horizontally on a magnetic rail. In 1987 Germany conducted an assessment comparing Saenger II with LART and found that LART would cost about half as much to develop (\$7 billion to \$8 billion for LART compared to \$14.5 billion for Saenger II with HORUS). The assessment also concluded that LART is an alternative and competitor to NASP.

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## Messerschmitt-Boelkow-Blohm/ERNO Raumfahrttechnik's Platform Orbiter

The Platform Orbiter (PLATO) aerospace vehicle concept is being developed by Messerschmitt-Boelkow-Blohm/ERNO Raumfahrttechnik (MBB-ERNO) of Bremen, Germany, to provide Europe with autonomy in the operation of unmanned, recoverable spacecraft. PLATO is envisioned as a small, unmanned, winged reentry vehicle that would be launched by the Ariane 4 rocket from Kourou, French Guiana, and retrieved after landing horizontally at a site in southern Europe. PLATO's mission would be to conduct material and life science experiments in space and to develop materials, structures, and navigation and control techniques for future spacecraft. Figure I.1 shows MBB-ERNO's PLATO vehicle being launched from the Kourou Space Center by the Ariane 4 rocket booster.

Figure I.1: Mbb-Erno's PLATO Vehicle and the European Space Agency's Ariane 4



Source: Messerschmitt-Boelkow-Blom/ERNO Raumfahrttechnik.

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PLATO would be about 39 feet in length in a rectangular wing configuration or about 47 feet in length in a delta wing configuration and would have a wingspan of about 21 feet. PLATO would weigh about 5.5 tons at launch and would be able to deploy a payload of between 0.8 and 1.1 tons.

The PLATO concept was a result of Europe's desire for the European Space Agency's European Retrievable Carrier (EURECA)<sup>1</sup> operations not to be dependent on the U.S. space shuttle. The Europeans were concerned that opportunities for EURECA-type missions would be reduced or discontinued due to the uncertainty surrounding resumption of U.S. space shuttle operations after the Challenger accident in January 1986, the possibility that other payloads would be given higher priority when space shuttle operations resumed, and the lack of an adequate European launch and retrieval vehicle for EURECA. Europe's desire for autonomy led to initial studies of methods for launching EURECA by Ariane 4 and servicing the spacecraft in orbit by the Hermes spaceplane. However, the U.S. space shuttle would still have had to retrieve EURECA, since Hermes would not have this capability. The PLATO vehicle would be able to retrieve EURECA without relying on the U.S. space shuttle and develop it as a completely autonomous European system.

According to MBB-ERNO officials, EURECA would be integrated into a winged reentry vehicle, launched by Ariane 4 from Kourou, and retrieved after a horizontal landing in Europe. Some of EURECA's systems (such as power, attitude and orbit control, and communications and data handling systems) could be used for control of PLATO's return flight.

PLATO's unusual design features the positioning of its main landing gear in the two rear and single forward vertical tails. This design would require that PLATO perform a roll maneuver of 180 degrees before landing, since the landing gear would be located on the upper side of the vehicle during the reentry and hypersonic flight phases. This feature was introduced to simplify the heat shield design.

Objectives of further concept development of PLATO were to keep costs low; minimize the application of advanced technologies and use existing

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<sup>1</sup>EURECA is free-flying, reusable, self-sufficient space platform designed to conduct scientific experiments and industrial activities in a space environment. EURECA is intended to fully utilize microgravity facilities and evaluate European space station technologies. EURECA 1 is currently scheduled to be deployed on its first mission by the U.S. space shuttle Discovery in August 1992 and retrieved by the space shuttle Columbia 6 to 10 months later. However, according to the National Aeronautics and Space Administration, as of July 1991, these dates were currently under review, and, as a result, the manifest dates for the space shuttles might change.

techniques, materials, and components whenever possible to achieve a first operational mission between 1995 and 2000; and utilize the experience gained during the preparation of EURECA's first mission and other programs for ground and flight operations. The first step in the development process was a critical appraisal of PLATO's configuration and an assessment of its performance.

Phase A1 of a feasibility study of the PLATO concept was conducted between November 1987 and February 1989 for the Federal Ministry for Research and Technology and concentrated on obtaining basic data. Phase A1 consisted of computer simulations of ascent, reentry, and return flight profiles; preliminary thermal analyses; and a series of low-speed wind tunnel tests at the Rheinland-Westfalia Technical University of Aachen. This phase of the study was managed by the German Aerospace Research Establishment and funded by the Ministry at a cost of about \$334,000. Four MBB-ERNO engineers worked full-time on the PLATO concept during Phase A1.

The results of the ascent simulation showed that it was feasible to launch PLATO by Ariane 4. Results from the reentry simulation indicated that PLATO's cross-range landing capability would be about 1,240 miles and that relatively low heat fluxes could be expected, since PLATO would decelerate at high altitude. This situation would result in low vehicle surface temperatures that would allow PLATO to be manufactured from less exotic materials. Results obtained from low-speed wind tunnel tests indicated that a rectangular wing version of PLATO is the preferred configuration, since it has better aerodynamic characteristics than a delta wing configuration and would be less expensive to build. However, wind tunnel tests at supersonic and hypersonic speeds are required to confirm the superiority of the rectangular wing configuration. Company officials reported that the test results obtained so far are promising and will allow further development of the PLATO concept.

In October 1988 MBB-ERNO officials submitted a proposal for Phase A2 (from November 1988 to April 1990) to the German Space Agency to study supersonic aerodynamics, critically analyze every stage of PLATO's development, and assess its feasibility. Although some Agency officials expressed interest in pursuing the PLATO concept, funding was not available at that time. As of June 1991, the PLATO project was on hold. However, a company official said that the project could soon be revived.

Over the past year, the PLATO concept has been a low-level effort involving one MBB-ERNO engineer part-time to study technology applications, specific uses, and research applications. Future work on PLATO would assess hypersonic aerodynamics. Although not part of the German Research Association's Special Research Field Project, several German universities have expressed interest in participating in the PLATO project as subcontractors.

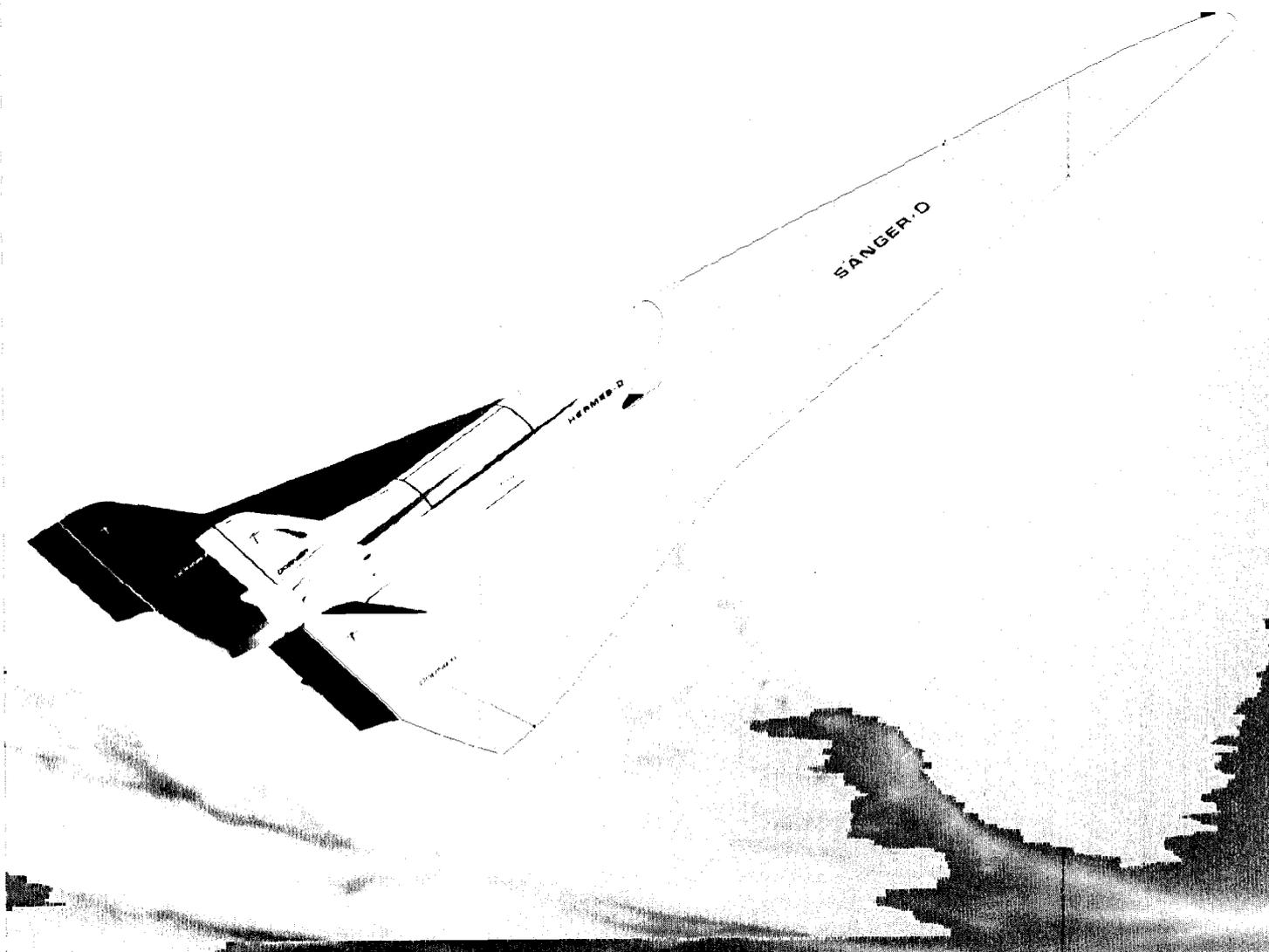
According to a MBB-ERNO official, the PLATO concept would probably be funded in the future from the Federal Ministry for Research and Technology through the German Space Agency. Phase A2, if approved, could cost about \$569,000. Phase A2 would be managed by the Agency.

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## Dornier's Saenger D

Dornier's Saenger D concept, a two-stage-to-orbit space launch vehicle, is a variation of Messerschmitt-Boelkow-Blohm's Saenger II. Dornier is proposing a staging of Saenger II, since the technology required for air-breathing engines has not progressed far enough in Europe. Saenger D's second-stage rocket engines would be started when the thrust of the first-stage ramjet engines declined beyond Mach 4. Ramjets become inefficient above Mach 6.5, since energy is lost in slowing down the air flow to subsonic speeds in the combustion chamber. The second-stage rocket engine would be fed from the propellant tanks of the first stage until separation occurred at approximately Mach 7. Figure I.2 shows Dornier's Saenger D concept with a Hermes-derived second stage.

Figure I.2: Dornier's Saenger D



Source: Dornier.

Saenger D would be about 266 feet long and 131 feet wide and have a takeoff weight of 415 tons. The nose cone and winglet assemblies would be made of fiber-reinforced carbon structures and reinforced ceramic structures that are able to withstand temperatures of 1,300 to 1,600 degrees Celsius.

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## Dornier's European Advanced Rocket Launcher II

The European Advanced Rocket Launcher (EARL) system is intended to serve as a follow-on to the Ariane 5 launch vehicle and the Hermes spaceplane and as a bridge to a Saenger II-class space transportation system. Dornier began the original EARL concept study in 1986 under a Federal Ministry for Research and Technology contract. In 1988 Dornier began a new study known as EARL II in cooperation with Maschinenfabrik Augsburg-Nuernberg Technologie and Messerschmitt-Boelkow-Blohm. The study concluded that EARL II could lead to significant savings compared with Hermes operational costs. However, the future of the EARL II program will depend on the outcome of government planning for Germany's Fifth Space Program.

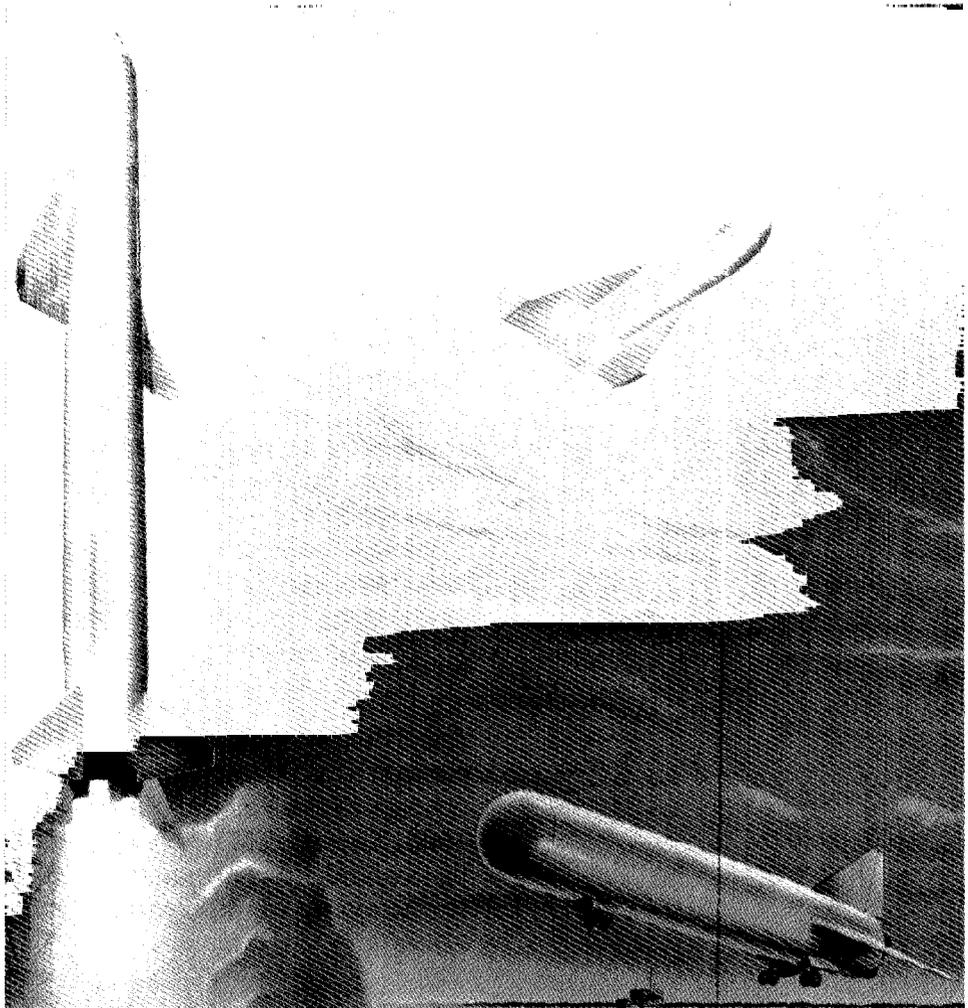
The first flight of EARL II is proposed for 2006, and EARL II is expected to be ready to replace the Ariane 5 and Hermes space transportation system by 2008. However, Ariane 5 and Hermes are each expected to have a life expectancy of about 15 to 20 years. This proposed schedule implies that Ariane 5 and Hermes would be retired 10 years prematurely.

The primary mission of EARL II would be to service the second-generation European space station (after Columbus). This would be accomplished by approximately 5 manned and 7 to 10 unmanned flights per year.

The EARL II concept study for a two-stage cryogenic, vertical takeoff and horizontal landing space transportation system combines previous studies of the Ariane-Derived Vehicle and EARL. EARL II is being designed primarily as a manned system with a second-stage spaceplane four times heavier than Hermes that will carry four astronauts and 5 tons of cargo to and from an orbital space station. Its unmanned cargo version would be able to launch a 5.5-ton payload into geosynchronous transfer orbit or a 16.5-ton payload into low earth orbit. The manned version would be completely recoverable, whereas the cargo stage of the unmanned version, derived from the cryogenic stage of the Ariane 5 and equipped with a cryogenic engine modeled after the HM60, would be expendable.

Two configurations were considered, one involving tandem stages and the other parallel stages. The tandem configuration was abandoned because of somewhat less flexibility than the parallel configuration. Figure I.3 shows the EARL II manned and unmanned parallel launch vehicles.

**Figure I.3: Dornier's EARL II Manned and Unmanned Parallel Launch Vehicles**



Source: Dornier.

In the manned version, the parallel configuration would consist of a 369-ton first stage and a 127-ton spaceplane, which would result in a takeoff weight of 496 tons. The spaceplane is being designed with a delta-shape wing and a 18-foot diameter fuselage that will enclose a cabin for four astronauts and space for 5 tons of cargo. Cryogenic fuel tanks would be located on either side of the cabin. The parallel first stage would be powered by four Advanced Future Topping Cycle 1500 cryogenic engines and the spaceplane by one Advanced Future Topping Cycle 1500 engine and two maneuvering engines.

The EARL II study is emphasizing gradual advances in available technology or in technology already under development to limit the project's risks and increase its cost-effectiveness. Dornier, Maschinenfabrik Augsburg-Nuernberg Technologie, and Messerschmitt-Boelkow-Blohm officials have concluded that the technological advances required for an air-breathing first stage or single-stage-to-orbit space launch vehicle are too expensive.

EARL II's technology development includes the following key elements:

- reusable cryogenic fuel tanks for liquid oxygen and liquid hydrogen (the first-stage fuel tanks would be based on the Ariane 5 design);
- a propulsion system for both stages based on Advanced Future Topping Cycle engine high-pressure technology currently being developed by Messerschmitt-Boelkow-Blohm;
- first-stage aerodynamics and return systems;
- separation methods for the reusable parallel stage;
- parallel-stage fuel transfer; and
- further development of the Hermes-based crew rescue system, heat-protection system, and orbiter aerothermodynamic and aerodynamic design.

According to a Dornier official, four to five people worked on the EARL II concept study. Dornier officials made a final presentation on the EARL II concept to the Federal Ministry for Research and Technology in October 1990. However, Ministry officials indicated that no more money would be available to continue the EARL II program. A Dornier official said that the company would try to continue the effort with internal funding.

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# Glossary

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<b>Aeroballistic</b>	The flight characteristics of projectiles or high-speed vehicles in the atmosphere.
<b>Aerothermodynamic</b>	A branch of thermodynamics relating to the heating effects associated with the dynamics of a gas, particularly the physical effects produced in the air flowing over a vehicle during launch and reentry.
<b>Air-Augmented Rocket</b>	A rocket engine in which air is brought on board and is mixed with the rocket's exhaust to increase thrust. The rocket may be operated fuel-rich with the extra fuel being burned by the air for additional thrust.
<b>Air-Breathing</b>	An aerodynamic vehicle engine that requires air for combustion of its fuel.
<b>Air-Breathing Propulsion Test Cell</b>	A ground test facility used to test an aircraft engine that requires air for combustion of its fuel.
<b>Airflow</b>	A flow or stream of air.
<b>Air-Turboramjet</b>	An air-breathing engine similar to a ramjet except that the air is compressed in an axial flow fan before being mixed with hydrogen (or some other hydrocarbon fuel) and burned in the ramburner. Combustion products are passed through a heat exchanger, which heats the hydrogen fuel, and then are expanded through the exhaust nozzle, creating the thrust. The heated hydrogen passes through an axial flow turbine, which drives the fan, and then is injected into the ramburner, where the heated hydrogen is burned. Temperature limitation caused by turbine blade materials is avoided, since combustion products are not passed through the turbine. Air-turboramjets can perform well from Mach 0 to 6.
<b>Algorithm</b>	A step-by-step procedure for solving a mathematical problem.

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<b>Angle of Attack</b>	The acute angle between the direction of the relative airflow and the chord (i.e., the straight line joining the leading and trailing edges of an airfoil) of the test model.
<b>Arc-Heated</b>	The heating of the test gas by the heat energy from an electric arc, which has a very high temperature and concentration of heat energy. It is also referred to as electric arc-heated.
<b>Bar</b>	A unit of pressure equal to about 1 million dynes per square centimeter ( $1.01325 \times 10^6$ dynes/cm <sup>2</sup> ). One bar is Normal Atmospheric Pressure.
<b>Blowdown Wind Tunnel</b>	An open-circuit wind tunnel in which gas stored under pressure is allowed to expand through a test section to provide a stream of gas or air to test a model. The gas then escapes into the atmosphere or into an evacuated chamber. Test times are finite and usually last from a few seconds to minutes.
<b>Boundary Layer</b>	A region of the flow of a retarded viscous fluid near the surface of a body that moves through a fluid or past which a fluid moves.
<b>Brazing</b>	The process of joining two pieces of metal by fusing a layer of a nonferrous alloy between the adjoining surfaces. The alloy melts at a lower temperature than the metals being joined.
<b>Carbon-Carbon</b>	A material that consists of 100-percent carbon fibers in a carbon matrix. The material does not contain any binders or epoxy and is coated with a ceramic material. Carbon-carbon is extremely lightweight and is being considered for use on aerospace plane thermal protection systems.
<b>Celsius</b>	A temperature scale in which the freezing point of water at standard atmospheric pressure is 0 degrees Celsius and the corresponding boiling point is 100 degrees Celsius. Zero degrees Celsius equals 273.16 degrees Kelvin.

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Cerasep	A fiber and ceramic matrix developed by the European Propulsion Company to improve performance of monolithic ceramics.
Combined-Cycle Engine	Engine concepts using some combination of air-breathing and rocket components which are integrated into a single propulsion system.
Composite Materials	Structural material made of two or more different materials such as carbon-fiber reinforced epoxy resin.
Computational Fluid Dynamics	A tool for predicting the aerodynamics and fluid dynamics of air around flight vehicles by solving a set of mathematical equations with a computer. Also known as numerical aerodynamic simulation, computational fluid dynamics is used in aerospace vehicle research and development programs to improve the understanding of hypersonic flow physics and as an aerospace vehicle design tool.
Cryogenic	Operating at extremely low temperatures.
Dyne	A unit of force sufficient to accelerate 1 gram 1 centimeter per second squared ( $1 \text{ g} \times 1 \text{ cm/s}^2$ ) or $2.248 \times 10^{-6} \text{ lb}$ .
Ejector Ram-Rocket	Basically a ram-rocket engine with two primary differences. First, the rocket (or rockets) is (or are) used to provide an ejector effect at Mach 0 that draws ambient air into the engine. Second, the rocket is operated without excess fuel, thus requiring additional fuel in the engine's combustor downstream of the rocket. The fuel added in the combustor does not have to be the same fuel used in the rocket. Compared to just a rocket, the ejector ram-rocket engine provides high thrust from Mach 0 to 6 or higher.
Enabling Technology	A critical technology that makes development and demonstration of an aerospace vehicle possible. Enabling technologies may include an air-breathing propulsion system; advanced materials that are high-strength, lightweight, able to withstand high temperatures, and fully reusable; a fully integrated engine and airframe; use of computational fluid

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dynamics and supercomputers for aerodynamic, structural, and propulsion system design; and efficient use of hydrogen both as a fuel and to actively cool the airframe.

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**Enthalpy**

The total energy (heat content) of a system or substance undergoing change from one stage to another under constant pressure. Enthalpy is expressed as the sum of the internal energy of a system plus the product of the system's volume multiplied by the pressure exerted on the system by its surroundings. Enthalpy is also known as heat content, sensible heat, and total heat.

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**Free-Piston**

A technique in which a single stroke of a heavy piston in a shock tunnel compresses the driver gas to raise its pressure and temperature before rupturing the main shock tube diaphragm. When helium driver gas is used, this technique allows routine operation of the shock tunnel in the reflected shock mode with test section stagnation enthalpy values approaching orbital velocities (8 kilometers per second).

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**Geostationary**

A satellite orbit traveling from west to east at speeds that allow it to remain fixed over a given place on the earth's equator at approximately 22,300 miles in altitude. A geostationary satellite makes one revolution in 24 hours, synchronous with the earth's rotation.

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**Gun Tunnel**

A hypervelocity wind tunnel in which a shock wave generated in a shock tube ruptures a second diaphragm in the throat of a nozzle at the end of a tube. Gases emerge from the nozzle over the model in the test chamber and into a vacuum dump tank. Speeds achieved in a gun or shock tunnel typically range from Mach 6 to 25.

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**Heat Exchanger**

Any device that transfers heat from one fluid to another or to the environment.

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**Heat Transfer**

The transfer or exchange of heat by radiation, conduction, or convection within a substance and between the substance and its surroundings.

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Hotshot Tunnel	A hypervelocity wind tunnel in which electrical energy is discharged into a pressurized arc chamber, increasing the temperature and pressure so that a diaphragm separating the arc chamber from an evacuated chamber is ruptured. The heated gas from the arc chamber is then accelerated in a conical nozzle to provide flows with Mach numbers of 10 to 27 for durations of 10 to 100 milliseconds.
Hypersonic	A range of speed that is five times or more the speed of sound in air.
Hypersonics	A branch of aerodynamics that deals with the flow of air and other gaseous fluids at speeds greater than five times the speed of sound in air. Hypersonics may also refer to the technologies associated with aerospace vehicles flying at such speeds.
Hypervelocity	A range of speed that is about 12 times or more the speed of sound in air.
Intermittent Wind Tunnel	A wind tunnel in which energy is stored, usually as compressed air, and then released suddenly to force a large quantity of air through the small throat of the nozzle and over the test model in the test section in a short period of time. The test gas is then captured in a vacuum dump tank or released into the atmosphere.
Isentropic	Constant entropy or without change in entropy (a measure of the unavailability of energy).
Kinetics	A branch of science that deals with the effects of forces on the motion of material bodies or with changes in a physical or chemical system.
Liquefaction	A change in the phase of a substance to the liquid state. Liquefaction usually involves a change from the gaseous to the liquid state, especially of a substance that is a gas at normal pressure and temperature.

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<b>Liquid Air Cycle Engine</b>	Basically a rocket engine in which the oxidizer is liquid air obtained by liquefaction of the air entering the air-breathing inlet. The heat sink capacity of liquid hydrogen is used in a heat exchanger to liquefy the flow of air. The liquid air is then pumped to a conventional rocket combustion chamber, which is used to burn the liquid hydrogen. This engine has variations in the method used to obtain the power to pump the air and hydrogen to high pressures. Theoretically, this engine can perform well from Mach 0 to 8. A liquid air cycle engine is the same as a liquid air rocket engine.
<b>Liquid Air Rocket</b>	Basically a rocket engine in which the oxidizer is liquid air obtained by liquefaction of the air entering the air-breathing inlet. The heat sink capacity of liquid hydrogen is used in a heat exchanger to liquefy the flow of air. The liquid air is then pumped to a conventional rocket combustion chamber, which is used to burn the liquid hydrogen. This engine has variations in the method used to obtain the power to pump the air and hydrogen to high pressures. Theoretically, this engine can perform well from Mach 0 to 8. A liquid air rocket engine is the same as a liquid air cycle engine.
<b>Mach Number</b>	A number representing the ratio of the speed of an object to the speed of sound in the surrounding atmosphere. An object traveling at the local speed of sound is traveling at Mach 1.
<b>Massively Parallel Computing</b>	The simultaneous computation of several parts of a problem on a computer that can carry out more than one logic or arithmetic operation at one time. The computer usually consists of 100 or more processors.
<b>Millisecond</b>	One-thousandth of a second.
<b>Navier-Stokes Codes</b>	Computer software that contains the mathematical equations of motion for a viscous fluid.
<b>Nozzle</b>	The exit duct of a wind tunnel or exhaust duct of an engine used for accelerating a fluid and producing a desired direction, velocity, or shape of discharge. The fluid's pressure decreases as it leaves the nozzle. The

nozzle usually has an increasing cross-section in the direction of the flow.

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**Observables**

Characteristics of a flight vehicle (such as distance, speed, and shape) that can be seen electronically, optically, or thermally. Composite materials can absorb radar waves, thus reducing the returned radar signal.

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**Piston-Driven**

A type of shock tunnel in which energy is created by a piston being fired (or driven) down a cylinder, compressing the test gas ahead of it. The pressure and temperature of the test gas is increased, creating a shock.

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**Plasma-Jet Tunnel**

A wind tunnel that has the capability of developing the highest temperature (approximately 35,000 degrees Fahrenheit) and the longest run time (several minutes) of any hypervelocity tunnel. The plasma-jet tunnel is arc-heated and capable of achieving relatively high velocities (up to 20,000 feet per second), but few have been built or planned for obtaining Mach numbers above 10.

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**Platelet Technology**

Very small and intricate passages for transporting a cooling fluid through a hot aerospace vehicle component by constructing the component from a series of very thin sheets of the desired material. Each sheet is photoetched to create the holes or passages desired. The sheets are then placed on top of one another and fused together. The advantage of this technique, particularly for development and experimental work, is that the designs can be easily modified and a new part can be made very quickly. Platelet technology is being considered for use in aerospace vehicles as a thermal control system.

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**Ramjet**

An air-breathing engine that compresses (or rams) the high-speed air entering the inlet by efficiently slowing it down to subsonic speeds, at which time it is burned with the fuel in a combustion chamber (ramburner). High-temperature combustion gases are expanded through an exhaust nozzle at high speed, creating the thrust. A ramjet is capable of efficient operation at supersonic speeds of about Mach 2 to 6.

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**Ram-Rocket**

A rocket engine in which an air-breathing inlet and duct system are added, permitting atmospheric air to be introduced at the exit of the

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rocket combustion chamber. By operating the rocket engine with more fuel than necessary to use the rocket's oxidizer, the rocket's hot combustion products can be mixed with the atmospheric air where the excess fuel is burned, creating additional high-temperature combustion products. A ram-rocket engine provides high thrust at subsonic and supersonic conditions while retaining the rocket's ability to produce thrust at static (Mach 0), hypersonic, and orbital conditions.

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**Rapid Solidification Technology**

A process in which molten metals such as titanium and aluminum are transformed into a very fine powder, which is then solidified. The resulting alloy (ti-aluminide) demonstrates much higher strength and stiffness at high temperatures compared to conventional titanium alloys. Moreover, ti-aluminide has one-half the weight of the material previously used at these high temperatures.

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**Real Gas Effects**

A gas behavior or phenomena resulting from the interactions of gas molecules.

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**Reynolds Number**

A dimensionless number used as an indication of scale of fluid flow. It is significant in the design of a model of any system in which the effect of viscosity is important in controlling the velocities or the flow pattern of a fluid. Reynolds Number is equal to the density of a fluid times its velocity times a characteristic length divided by the fluid viscosity.

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**Scramjet**

A supersonic combustion ramjet air-breathing engine in which air flows through the combustion chamber at supersonic speeds. Hydrogen is injected into the combustion chamber where it is ignited by the hot air. At very high flight speeds (Mach 6 and above), the supersonic speeds in the combustor reduce the internal pressures and temperatures, allowing efficient combustion of the hydrogen fuel and a reduction in the weight of the combustor. The hot gases are further accelerated through the exhaust nozzle, creating the thrust. Theoretically, scramjets provide efficient operation at hypersonic speeds of about Mach 4 to 25 (orbital velocity).

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**Sepcarbinox**

A composite material developed by the European Propulsion Company consisting of a carbon fiber-reinforced matrix combined with alumina and silicon carbide. The material is resistant to oxidation.

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Shock Tube	A wind tunnel for conducting tests at hypervelocity speeds in which fluid (such as air or some other test gas) at high pressure, usually involving rapid combustion to increase energy, is released by rupturing a diaphragm and accelerated through an evacuated working section (test chamber) containing the model.
Shock Tunnel	A hypervelocity wind tunnel in which a shock wave generated in a shock tube ruptures a second diaphragm in the throat of a nozzle at the end of a tube. Gases emerge from the nozzle over the model in the test chamber and into a vacuum dump tank. Speeds achieved in a shock tunnel typically range from Mach 6 to 25.
Shock Wave	A fully developed compression wave of large amplitude, across which density, pressure, and particle velocity change drastically.
Sonic (Velocity)	The speed of sound in air (761.5 miles per hour at sea level).
Stagnation Enthalpy	The total energy or heat content of a system generated when the flow is brought to rest (zero velocity) isentropically at a stagnation point.
Subsonic	A range of speed below the speed of sound in air.
Supercomputer	A computer with the highest processing speed in any given period of time. A supercomputer is part of a high-performance computing system that is at the forefront of the computing field in terms of computational power, storage capability, input/output bandwidth, and software. These systems include high-speed vector and pipeline machines, special purpose and experimental systems, scalable parallel architectures, and associated mass storage systems, input/output units, and systems software.
Supersonic	A range of speed between about one and five times the speed of sound in air.

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Test Cell	A horizontal test stand for an air-breathing or rocket engine surrounded on three sides by a shelter providing protection from weather and limited protection from an accidental explosion.
Test Chamber	The test section of a wind tunnel.
Thrust	The force exerted in any direction by a fluid jet.
Transonic	A range of speed between about 0.8 and 1.2 times the speed of sound in air.
Trisonic	Three ranges of speed capability in a wind tunnel (such as subsonic, transonic, and supersonic).
Turboexpander Ramjet	An air-breathing engine that is the same engine as an air-turboramjet. However, a turboexpander ramjet differs from a turboexpander engine, which is essentially an air-turboramjet with an emphasis on operation from Mach 0 to 3. The air in a turboexpander ramjet is compressed by the axial flow fan to a higher pressure level than in the air-turboramjet, which provides the turboexpander ramjet with improved efficiency at lower flight speeds. Because combustion products are not passed through the turbine, the temperature limitation caused by turbine blade materials is avoided.
Turboexpander-Ram-Rocket	An air-breathing engine that combines the features of a turboexpander engine and a ram-rocket engine. A fan is added to the engine to compress the incoming air for improved fuel efficiency at low Mach numbers. The fan is removed from the airstream above Mach 3 where the engine operates as a ram-rocket. The fan is driven by a turbine. The turbine is powered by hydrogen heated in a heat exchanger in the combustion chamber. The rocket engine is not operated until the fan is removed from the airstream at higher Mach numbers, since the fan provides the airflow necessary for production of thrust at low flight speeds. Although it is heavier than the more simple ram-rocket engine, the turboexpander ram-rocket engine provides improved efficiency, which

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offsets its increased weight, for applications with significant flight time spent at low Mach numbers.

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### Turbofan

An air-breathing engine, similar to a turbojet, in which a portion of the compressed air bypasses the combustor and turbine. The remaining compressed air enters the combustor. The compressed air is then mixed with the fuel, burned, and expanded through the turbine. The power from the turbine is used to drive the compressor. Hot gases exiting from the turbine and compressed bypass air can be mixed and expanded through an exhaust nozzle or separate exhaust nozzles to produce the thrust. When fuel is added and burned downstream of the turbine, a turbofan engine can operate efficiently from Mach 0 to 2.5.

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### Turbofan-Ramjet

An air-breathing engine consisting of a turbofan engine mounted within a ramjet duct. At low speeds, the engine operates as a turbofan. Between Mach 1 and 2, the ramburner begins to operate, providing a greater portion of the thrust until the turbofan is shut down at speeds of approximately Mach 3. At that point, the ramjet provides all of the thrust. During all operating modes, the high-temperature combustion gases are expanded through the exhaust nozzle to produce the thrust. A turbofan-ramjet engine provides the efficiency of a turbofan during takeoff and low-speed flight and the efficiency and high thrust of a ramjet during high-speed flight (up to Mach 6).

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### Turbojet

An air-breathing engine in which air is compressed by a compressor before it enters a combustor. Air is then mixed with fuel, burned, and expanded through a turbine. The power from the turbine is used to drive the compressor. Hot gases exiting from the turbine are expanded through an exhaust nozzle to produce thrust. When fuel is added and burned downstream of the turbine, a turbojet engine can operate efficiently from Mach 0 to 3.

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### Turbojet-Ramjet

An air-breathing engine consisting of a turbojet engine mounted within a ramjet duct. At low speeds, the engine operates as a turbojet. Between Mach 1 and 2, the ramburner begins to operate and provides a greater portion of the thrust until speeds of approximately Mach 3.5, when the turbojet is shut down and the ramjet provides all of the thrust. During all operating modes, high-temperature combustion gases are expanded through the exhaust nozzle to produce thrust. A turbojet-ramjet engine

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provides the efficiency of a turbojet during takeoff and low-speed flight and the efficiency and high thrust of a ramjet during high-speed flight (up to Mach 6).

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**Turboramjet**

An air-breathing engine consisting of a turbojet engine mounted within a ramjet duct. Intake air is compressed at low speeds by a compressor driven by a turbine and at high speeds by the ram effect of the engine moving through the air. At low speeds, the engine operates as a turbojet. Between Mach 1 and 2, the ramburner begins to operate and provides a greater portion of the thrust until speeds of approximately Mach 3.5, when the turbojet is shut down and the ramjet provides all of the thrust. During all operating modes, high-temperature combustion gases are expanded through the exhaust nozzle to produce thrust. Like the turbojet-ramjet, the turboramjet engine provides the efficiency of a turbojet during takeoff and low-speed flight and the efficiency and high thrust of a ramjet during high-speed flight (up to Mach 6). A turboramjet engine is the same as a turbofan-ramjet engine or turbojet-ramjet engine.

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**Turborocket**

A combined-cycle engine in which hot gases from a rocket operating with excess fuel are used to energize a turbine, which, in turn, drives a compressor for operation at speeds of Mach 0 to approximately 5. Gases exiting the turbine are mixed with air from the compressor, which burns the excess fuel. The resulting high-temperature gases are expanded through an exhaust nozzle, causing the thrust. A turborocket engine significantly reduces the need to carry oxidizer, thus reducing the weight of propellant needed to accelerate a vehicle to high Mach numbers and altitudes. A turborocket engine is a variant of an air-turboramjet engine.

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**Turborocket-Ram-Rocket**

A combined-cycle engine in which the air-breathing duct of a ram-rocket engine is added to the basic turborocket engine. This configuration allows operation of the turborocket-ram-rocket engine as a turborocket at speeds up to approximately Mach 4, where the compressor provides an efficiency advantage, and as a ram-rocket at speeds above Mach 4, where the compressor is inefficient and must be cooled. The combination of the two engines provides an improved overall efficiency and retains the ability of the ram-rocket to operate at very high Mach numbers.

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**Turborocket-Ramjet-Rocket**

A combined-cycle engine in which the air-breathing duct of a ramjet engine and a rocket are added to the basic turborocket engine. This configuration allows operation of the turborocket-ramjet-rocket engine as an air-augmented rocket up to approximately Mach 2.5 to 3, as a ramjet between about Mach 2.5 and 6, and as a pure rocket above Mach 6.

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**Turborocket-Rocket**

A combined-cycle engine in which a rocket is added to the basic turborocket engine. This configuration allows operation of the turborocket-rocket engine as an air-augmented rocket up to approximately Mach 2.5 to 3 and as a pure rocket above Mach 3.

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**Turboscramjet**

An air-breathing engine that has the same basic characteristics of a turboramjet with the additional capability of being able to operate as a scramjet at speeds above Mach 6. The scramjet in a turboscramjet engine is normally a dual-mode scramjet that operates as a subsonic combustion ramjet at speeds below Mach 6 and as a supersonic combustion scramjet at speeds above Mach 6. A turboscramjet engine provides the efficiency of a turbojet (or turbofan) during takeoff and subsonic flight, the efficiency and thrust of a ramjet from Mach 1 to 6, and the efficiency and thrust of a scramjet during hypersonic flight above Mach 6.

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**Wind Tunnel**

A ground test facility used to test flight characteristics of an aircraft by directing a controlled stream of air around a scale model and measuring the results with attached instrumentation.



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